FREQUENCY CHARACTERISTICS
OF THE
ELECTRON—TUBE OSCILLATION GENERATOR

BY

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THESIS

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1919

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THE GRADUATE SCHOOL

June 13, 1919

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Ray Stuart Quick

ENTITLED Frequency Characteristics of the Electron-Tube Oscillation Generator

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Electrical Engineering.

Ellery B. Paine
In Charge of Thesis

Ellery B. Paine
Head of Department

Recommendation concurred in*

Committee on Final Examination*

*Required for doctor's degree but not for master's

C O N T E N T S

I INTRODUCTION

1.Scope of Work. The development of the electron-tube (also called three-electrode vacuum tube,vacuum-tube,thermionic amplifier,audion,etc.) has brought to light many new and interesting problems. In using the tube as a source of continuous oscillations it is desirable to be able to predetermine the frequency, wave-form and amplitude characteristics. It is the purpose of this work to present the results of a study of the factors effecting the frequency of the generated oscillation.

2. Historical Review. The pioneer work with the electron tube dates back to the researches of Thos. A.Edison,upon the phenomena which has since been known as the Edison effect. Fleming, in 1896, investigated and described this effect in detail.(1). He also made applications of this phenomena to wireless detectors an 1904. (2). The addition of the grid is due to de Forest.(3). This latter three element device he named the "Audion".

Improvements in design and operation of the tube have been many and rapid. At present the tube has wide application in the fields of wireless telegraphy and telephony and in wire telephony. The most valuable applications are perhaps at present in the fields of wireless telegraphy reception,multiplex wire telephony,and in short range aeroplane and ship wireless telephony.

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(1).Proc. of the Royal Soc. 47,118 (1890),Phil. Mag. 42,52 (1896)

(2).U.S.Patent 803684--1915.

(3).U.S.Patent 879532--1908.

The production of undamped oscillations by means of the audion was first published by de Forest in 1915.(4). Langmuir and Hull of the General Electric Company (5),and Craft and Colpitts of the Western Electric Company (6),working with tubes developed in their respective laboratories, have secured and published results which show exceptional promise for the successful future of the device. Armstrong has published the results of a series of investigations of the application of the tube to wireless telegraphy.(7). Dr.Goldsmith of the College of the City of New York has also contributed to the literature on the subject.(8).

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(4).The Ultraudion as a Receiver of Undamped Waves.de Forest, Elec. Wld. Feb.20,1915.

(5).The Pure Electron Discharge.I.Langmuir, I.R.E. Sept. 1915.
The Dynatron. A.W.Hull. I.R.E. Feb. 1918.

(6).Radio Telephony. Craft and Colpitts, Proc. A.I.E.E. Mar. 1919.

(7).Some Recent Developments in the Audion Receiver. Armstrong, I.R.E. Sept. 1915.

(8).Radio Telephony. Dr. A.N.Goldsmith, Wireless Press,1918.

II THEORETICAL DISCUSSION OF PROBLEM.

1. General Principles of Operation. It has been known for a long time that an incandescent body radiates negative particles of electricity or electrons. This effect is not appreciable at atmospheric pressure but it does become noticeable at extremely low pressures. If a filament and plate be placed in a container from which the gas has been exhausted, and the filament then heated to incandescence, electrons will be given off. Those electrons striking the plate will raise it to a negative potential which will increase until the electrons are repelled as fast as they are emitted. When no plate is present the region around the filament will receive a charge due to the emitted electrons coming to rest. This fog of electrons builds up an insulation around the filament which prevents further increase in the emission. This effect is known as the "space charge".(9). The presence of even slight traces of residual gas in the tube practically eliminates this space charge effect since the gas becomes ionized by collision with the electrons and becomes conductive.

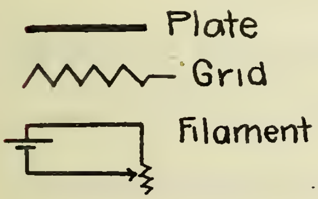

Fig. 1

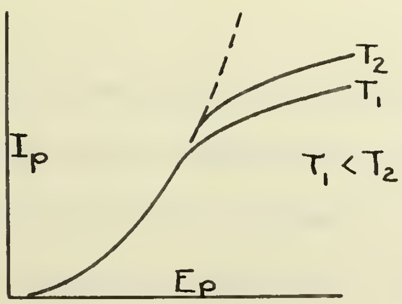

Fig. 2

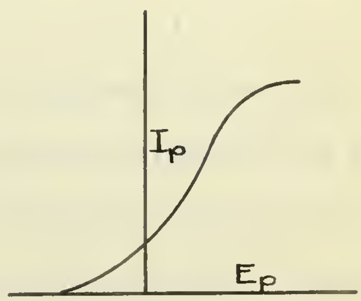

Fig. 3

To obtain any appreciable current from such a device it is necessary to connect a battery between filament and plate in

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(9). Space Charge Effect. G.E.R., 18: 158-160 and 330.

such a manner that the plate is positive with respect to the filament.This is due to the fact that negative charges are attracted by positive ones.The value of this thermionic current varies both with the temperature of the filament and the potential of the plate.The general relations of the elements of a tube are shown in fig.1. The influence of filament temperature and plate potential upon the current is shown in fig.2.

The addition of the grid between filament and plate is for the purpose of regulating the strength of the resultant electrostatic field at the plane of the filament.Since the grid is nearer to the filament than the plate is,variations of field of a given magnitude may be established at the plane of the filament by a much smaller change of grid potential than of plate potential. The effect,then,of grid potential variations is to produce changes of plate current which could otherwise only be produced by much larger variations of plate potential. This magnifying effect of grid potential changes has led to the name "amplifier" for the device. The influence of grid potential upon the plate current is shown in fig.3.

If the plate and grid circuits be coupled either by means of an inductance or a capacity or both,the primary disturbances in the grid circuit are produced in the plate circuit and returned amplified thru the coupling to the grid circuit. By effecting the coupling in the proper manner,so that positive plate current changes produce negative grid potential changes,the conditions of an unstable circuit ,similiar to the singing arc, are produced.The presence of parallel inductance and capacity in the

plate or grid circuit or both, will result in the production of oscillations. The characteristics of these oscillations will be controlled by the constants of the tube and of the circuits. With constant operating conditions the frequency and amplitude of the generated oscillations will not vary more than one-tenth of one per-cent in long periods of time.(10).

2. Circuits used.

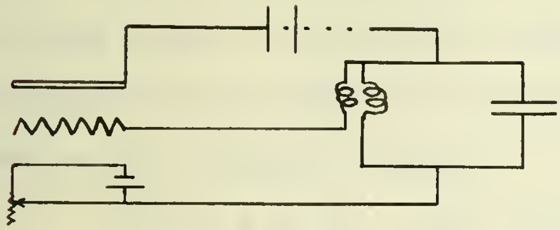

Fig.4

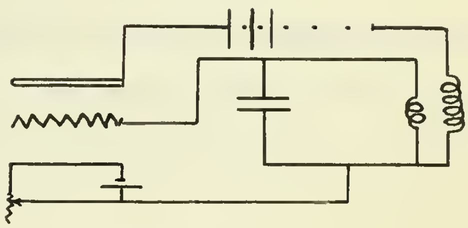

Fig.5

The circuit shown in fig.4 is suitable for the production of large oscillating currents. The grid acts analogously to the valve of a steam engine. It receives only sufficient energy to change it's potential. Oscillations will persist so long as the coupling is sufficient to transfer the required energy to the grid circuit.

The circuit shown in fig.5 differs from the first in that the oscillating circuit is in the grid circuit. All of the energy necessary to maintain oscillations is transferred thru the coupling.

3. Work of previous investigators. The four variables in the operation of the tube are as follows: plate potential (Ep), grid potential (Eg), plate current (Ip), and grid current (Ig). The relations between these variables may be expressed as follows:

(10). Bulletin #74, Bureau of Standards, P-219.

$I_p = \theta_1(E_g, E_p)$ $\qquad\qquad$ $I_g = \theta_2(E_g, E_p)$

These expression represent two surfaces. They have been named the characteristic surfaces of plate and grid currents respectively. Mathematical expressions for the equations of these surfaces are complex and beyond the scope of the present work. See articles by Bethenod (11), Latour(12), and Vallauri (13).

Any oscillations in the electron-tube circuit may be considered as taking place about a point upon the characteristic surface. If the oscillations be limited to such a degree that the operating range is plane, the characteristic may be expressed as a plane. Differentiating with respect to the time, the above equations for the surfaces become:

$$\frac{dI_p}{dt} = \frac{\partial \theta_1}{\partial E_g}\frac{dE_g}{dt} + \frac{\partial \theta_1}{\partial E_p}\frac{dE_p}{dt}$$
$$\frac{dI_g}{dt} = \frac{\partial \theta_2}{\partial E_g}\frac{dE_g}{dt} + \frac{\partial \theta_2}{\partial E_p}\frac{dE_p}{dt}$$

With the oscillations limited to a plane area, the partial derivatives, which express the slopes of their respective curves, become constants. They can then be expressed as follows:

$$\frac{\partial \theta_1}{\partial E_g} = K_1 , \quad \frac{\partial \theta_1}{\partial E_p} = K_2 , \quad \frac{\partial \theta_2}{\partial E_g} = K_3 , \quad \frac{\partial \theta_2}{\partial E_p} = K_4 ,$$

Marius Latour (14), using the above notation, arrives at an expression for the plate and grid currents as follows:

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(11). The Audion as an Auto Exciting Generator. J. Bethenod. "La Lumiere Electrique" Oct. 14, 1917. Ext. in Lon. Elec. 11/16/17.

(12). Theo. Discussion of the Audion. M. Latour. Lon. Elec. V. 78, Pp 281.

(13). The Audion. "L'Electrotecnia" Nos. 3 and 4, '17. Lon. Elec. Dec. 21, 1917.

(14). Theoretical Discussion of the Audion. M. Latour, Lon. Elec. V 78-Pp 281.

$I_p=K_1E_g+K_2E_p+C_1$ $\qquad I_g=K_3E_g+K_4E_p+C_2$ $\qquad$ (C_1 and C_2 = constants)

J. Bethenod (15), using Latour's notation, arrives analytically at an expression for the required minimum coupling as given:

$$K_4L(K_3+K_2)M+RC=-K^2K_1l$$

where:
L, l = Ind. of pl. and grid ccts. resp.
R = Res. of oscill. cct.
M = mutual ind. (couplimg)
$K = M^2/lL$

Vallauri (16), neglecting grid current and using Latour's notation gets the following for the required coupling:

$$M = -\frac{K_2L+(1+K_2R_1)RC}{K_1}$$

R_1 = series resistance, pl. cct.
Others as above.

E.V.L.Appleton (17), using principles of physics and mathematics, checks the results of Bethenod and Vallauri.

4. Mathematical Solution of the Circuit.

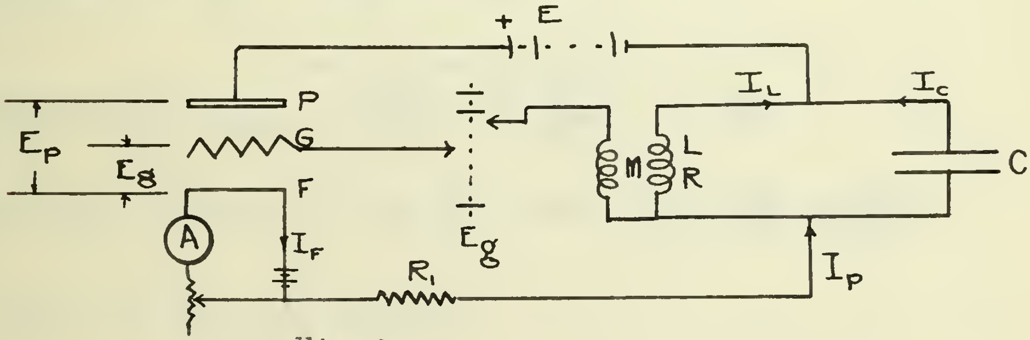


Fig. 6.

Grid current is neglected.

(15). See (11)

(16) " (13)

(17). Note on the Production of Continuous Electrical Oscillations by the Three-Electrode Vacuum-Tube. E.V.L.Appleton. The London Electrician, Dec. 27, 1918.

Oscillating circuit $\quad I_L R + L\frac{d(I_L)}{dt} = \frac{1}{C}\int Ic\ dt \quad$ (1)

Grid circuit $\quad Eg = -M\frac{d(I_L)}{dt} \quad$ (2)

Plate circuit $\quad E = Ep + IpR_1 + \frac{1}{C}\int Ic\ dt. \quad$ (3)

Summation $(I)=0 \quad Ip = Ic + I_L \quad$ (4)

Characteristic $\quad Ip = K_1 Eg + K_2 Ep + C_1 \quad$ (5)

$K_1 = \frac{\partial \theta_1}{\partial E_g}$, $K_2 = \frac{\partial \theta_1}{\partial E_p}$, $C_1 = 0$ (since when $Ep = Eg = 0, Ip = 0$)

The solution of the five simultaneous equations can be most easily effected by solving first for I_L and then expressing Ip in terms of I_L and transforming.

differentiating (1), $\quad R\frac{dI_L}{dt} + L\frac{d^2 I_L}{dt^2} = \frac{Ic}{C} \quad$ (6)

substituting (1) and (6) in (4), $\quad Ip = I_L + RC\frac{dI_L}{dt} + LC\frac{d^2 I_L}{dt^2} \quad$ (7)

substitute (1) and (6) in (3),

$$Ep = E - IpR_1 - \frac{1}{C}\int Ic\ dt = E - R_1\left(I_L + RC\frac{dI_L}{dt} + LC\frac{d^2 I_L}{dt^2}\right) - I_L R - L\frac{dI_L}{dt} \quad (8)$$

subst. (2,7,and 8) in (5),

$$I_L + RC\frac{dI_L}{dt} + LC\frac{d^2 I_L}{dt^2} = -K_1 M\frac{dI_L}{dt} + K_2\left(E - R_1\left(I_L + RC\frac{dI_L}{dt} + LC\frac{d^2 I_L}{dt^2}\right)\right.$$

$$\left. - I_L R - L\frac{dI_L}{dt}\right)$$ simplified, this becomes:

$$CL(1 + K_2 R_1)\frac{d^2 I_L}{dt^2} + (CR + K_1 M + K_2 R_1 RC + K_2 L)\frac{dI_L}{dt} + (1 + K_2[R_1 + R])I_L = K_2 E \quad (9)$$

This is of the standard form—, $aM^2 + bM + C = A$.

The solution of a differential equation of this type consists of two parts: the complementary function and the particular integral.

Complementary function:

$$aM^2 + bM + C = 0 \qquad M = \frac{-b + \sqrt{b^2 - 4ac}}{2a} = \alpha \pm \beta$$

Solution is:

$$I_L = A_1 e^{m_1 t} + A_2 e^{m_2 t}$$

$$= A_1 e^{(\alpha + \beta) t} + A_2 e^{(\alpha - \beta) t} \qquad (A_1 \text{ and } A_2 \text{ being arbitrary})$$

Particular integral:

type form: $$\frac{C}{(D - m_1)(D - m_2)} = \frac{C}{m_1 m_2} \quad (C = \text{a constant})$$

(See Murray, Diff. Eqs. Pp 73.)

Solution is: $$P.I. = \frac{B}{\alpha^2 - \beta^2}$$

General solution = comp. funct. + P.I.

$$I_L = A_1 e^{m_1 t} + A_2 e^{m_2 t} + \frac{B}{(\alpha^2 - \beta^2)}$$

$$= A_1 e^{(\alpha + \beta) t} + A_2 e^{(\alpha - \beta) t} + \frac{B}{(\alpha^2 - \beta^2)} \qquad (10)$$

Transformed to an expression in terms of Ip (from eq.7)

$$Ip = I_L + RC\frac{dI_L}{dt} + LC\frac{d^2 I_L}{dt^2}$$

$$= A_1 e^{(\alpha + \beta) t} + A_2 e^{(\alpha - \beta) t} + \frac{B}{(\alpha^2 - \beta^2)}$$

$$+ RC\left[(\alpha + \beta) A_1 e^{(\alpha + \beta) t} + (\alpha - \beta) A_2 e^{(\alpha - \beta) t}\right]$$

$$+ LC\left[(\alpha + \beta)^2 A_1 e^{(\alpha + \beta) t} + (\alpha - \beta)^2 A_2 e^{(\alpha - \beta) t}\right]$$

$$=A_1 e^{(\alpha+\beta)t}\left[1 + (\alpha+\beta)\left(RC + (\alpha+\beta)LC\right)\right]$$

$$+A_2 e^{(\alpha-\beta)t}\left[1 + (\alpha-\beta)\left(RC - LC(\alpha-\beta)\right)\right] + \frac{B}{(\alpha^2-\beta^2)}$$

$$= A' e^{(\alpha+\beta)t} + A'' e^{(\alpha-\beta)t} + \frac{B}{(\alpha^2-\beta^2)} \qquad (11)$$

To have oscillations, β must be imaginary ($b^2 - 4ac < 0$)

The form of the solution then becomes:

$$Ip = e^{\alpha t} A \sin(\beta t + \phi) + \frac{B}{(\alpha^2-\beta^2)} \qquad (A, \phi \text{ being arbitrary})$$

The coefficient of the exponent of e gives the attenuation. (12)
To have oscillations of a constant magnitude this coefficient must equal zero. To make this condition true the following relation holds:

$$\alpha = \frac{-b}{2a} = -\frac{CR + K_1 M + K_2 RR_1 C + K_2 L}{2CL(1 + K_2 R_1)} = 0$$

Since the denominator cannot equal infinity the numerator must be equal to zero.

$$0 = CR + K_1 M + K_2 RR_1 C + K_2 L$$

solving for M:

$$M = -\frac{K_2 L + CR(1 + K_2 R_1)}{K_1} \qquad (13)$$

This gives the relation for the coupling when steady oscillations are being produced.

The frequency of the oscillation equals $\sqrt{\frac{-4ac}{4a^2}}$

$$= j\sqrt{\frac{c}{a}} = j\sqrt{\frac{1 + K_2(R + R_1)}{CL(1 + K_2 R_1)}} = j\sqrt{\frac{1}{LC}} \cdot \sqrt{\frac{K_2 R}{1 + K_2 R_1} + 1}$$

The natural period of an oscillating circuit consisting of an inductance and a capacity is:

$$\frac{1}{2\pi}\sqrt{\frac{1}{LC}} = fo$$

The frequency in the case of the tube becomes fo x F (F being the expression

$$\sqrt{1 + \frac{K_2 R}{(1 + K_2 R_1)}}\ ) \qquad (14)$$

The magnitude of the direct current component of the plate current becomes:

$$\frac{B}{(\ \beta^2\ )} = \frac{B}{\frac{c}{a}} = \frac{A}{a} = \frac{K_2 E}{1 + K_2(R_1 + R\ )} \qquad (15)$$

The final form of the plate circuit current, when oscillations have constant amplitude is:

$$Ip = A \sin (f_o F\ t + \phi) + \frac{K_2 E}{1 + K_2(R_1 + R\ )}$$

$$= A \sin (f_o F\ t + \phi) + Idc. \qquad (16)$$

Analysis of this expression shows the plate circuit current to consist of the following factors:

(a) Oscillating sine component of amplitude "A" and frequency $f_o F$.

(b) Direct current component whose magnitude is Idc.

The value of M, given by equation (13) identically checks the value given by Vallauri who derived the expression from assumptions identical with the above. See foot note (16).

III APPARATUS AND METHODS

1. Electron-tubes Used. The electron-tubes used were the U.S.Signal Corps type V.T. #2 manufactured by the Western Electric Company.The rating was as follows: filament current,1.36 amps.; plate potential,300 volts;and grid potential,-20 volts.The rated output as an oscillation generator was approximately three watts.

2. Circuit Properties. The inductances and capacities used in the oscillating circuit consisted of two cylindrical coils, the moving coil telescoping into the larger,or fixed, coil.By placing the fixed coil in the plate circuit and the moving coil in the grid circuit, it was possible to obtain any value of mutual inductance between a maximum of 0.147 H. and a minimum of 0.0 H.The condensers used in the oscillating circuit were of tin foil in paraffined paper. The capacities ranged from one to three micro-farads.

3. Frequency Determinations. Frequency variation was determined by producing beats between the oscillating circuit under observation and a similiar constant frequency circuit oscillating nearly in unison with it.These two circuits were placed into inductive relation with an isolated coil which was connected to a telephone head-set.The beats were distinctly audible in the head-set yet the coupling between the two oscillating circuits was too loose to effect any appreciable reaction between them.The frequency of the so called "standard" circuit was maintained constant by keeping the operating conditions constant. Data were taken while varying only one operating condition at a time. These factors observed were plate potential,grid potential,filament current,and direct current component of the plate circuit current.

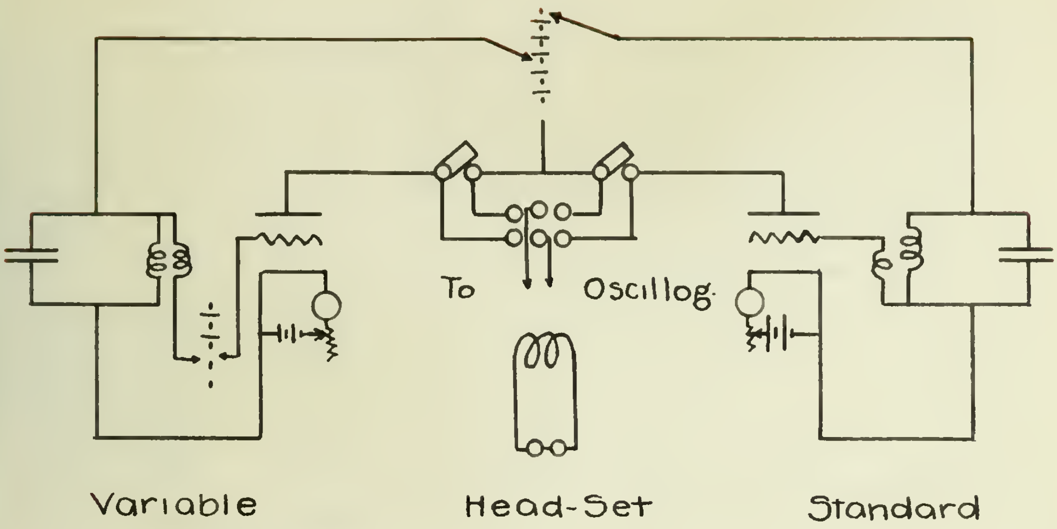
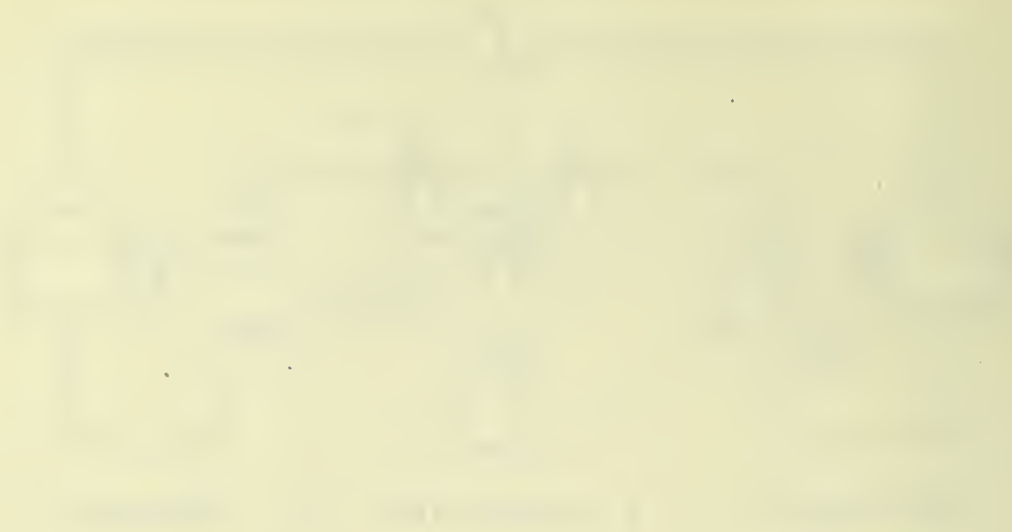
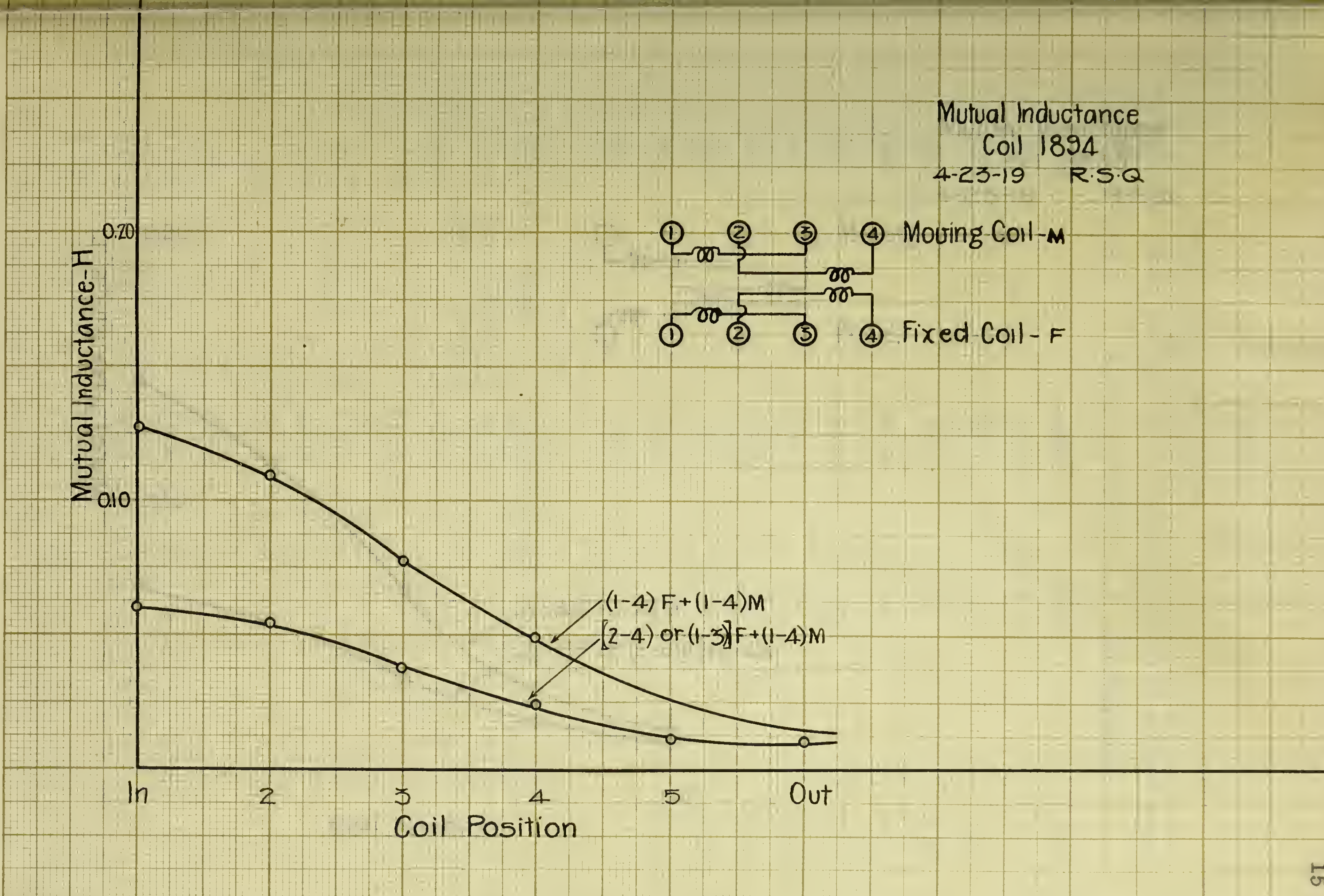


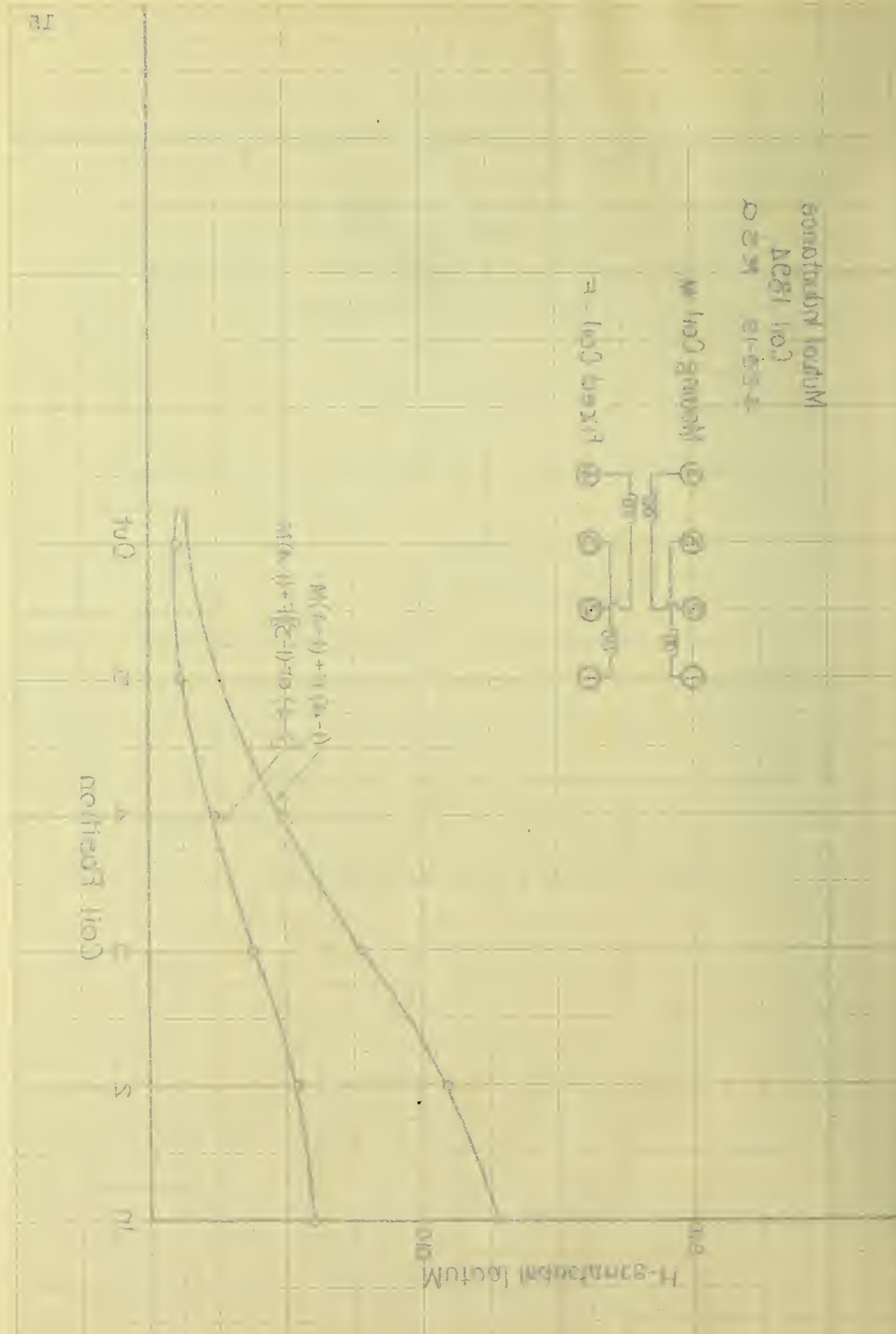
Fig.7

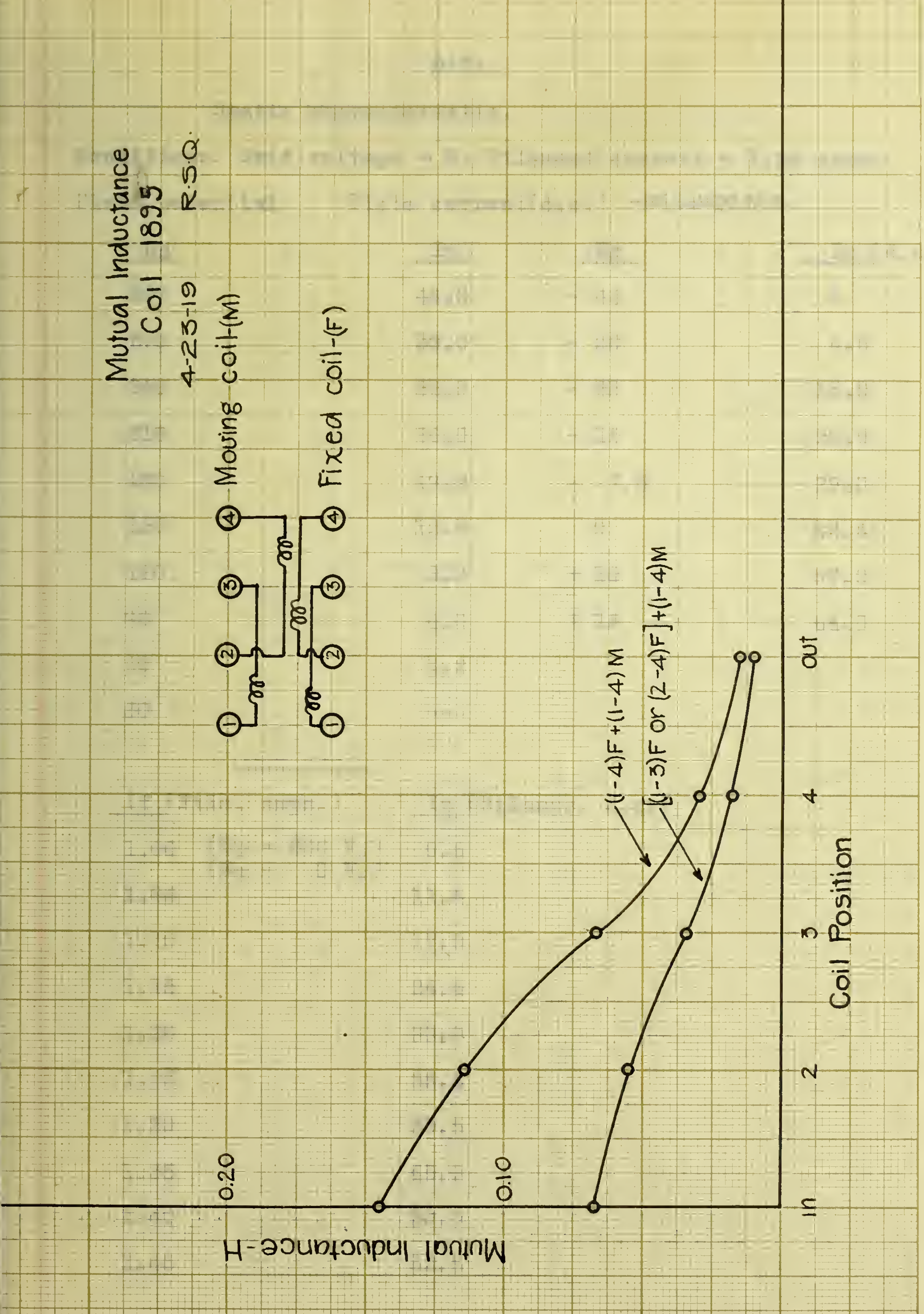
Working Circuit Used.

A common plate or "B" battery was used for the two circuits.Connections were made to an oscillograph in such a manner that either plate circuit current could be observed or both could be observed at the same time.The heterodyne beats could be observed by placing the oscillograph in the common battery lead.Independent filament current batteries were used.




Mutual Inductance
Coil 1894
4-23-19 R·S·Q
Moving Coil - M
Fixed Coil - F
Mutual Inductance-H
0.20
0.10
(1-4) F+(1-4)M
[(2-4) or (1-3)] F+(1-4)M
In
2
3
4
5
Out
Coil Position





Mutual Inductance
Coil 1895
4-23-19 R.S.Q.
Moving coil-(M)
Fixed coil-(F)
1 2 3 4
1 2 3 4
(1-4)F +(1-4)M
[(1-3)F or (2-4)F]+(1-4)M
Mutual Inductance-H
0.20
0.10
in
2
3
4
out
Coil Position

DATA

Static characteristic.

Conditions: Grid voltage = 0, Filament current = I.36 amps.

Plate potential   Plate current(d.c.) -milamperes.

Ep	Ip	Eg	Ip (d.c.)
300	44.0	- 45	0
270	39.0	- 30	4.6
240	32.0	- 20	15.0
210	26.0	- 15	20.9
180	19.2	- 7.5	29.0
150	13.5	0	43.4
120	8.3	+ 10	57.0
90	4.0	+ 15	64.0
60	1.2		
30	---		

If (Fila. amps.)		Ip (Milamps. d.c.)
1.00	(Ep = 300 V.) (Eg = 0 V.)	6.6
1.05		11.4
1.10		17.0
1.15		24.4
1.20		30.0
1.25		35.4
1.30		39.5
1.35		45.0
1.40		50.0
1.45		52.5

FREQUENCY VARIATION BY BEATS (132 CYC/SEC.)

Ep	Sec/60 beats.	Bts/sec.	Ip (d.c.) milamps.
300	37.3	1.609	31.0
270	38.2	1.570	28.5
240	38.6	1.554	26.5
210	39.2	1.530	23.7
180	40.0	1.500	20.4
150	41.0	1.464	16.6
120	41.2	1.456	13.3
90	41.3	1.450	7.0
60	----	-----	---

Variable tube

L = 0.268 H.

C = 5.35 M.F.

f = 132.8 cyc/sec.

Standard tube

L = 0.259 H.

C = 5.62 M.F.

f = 131.2 cyc/sec.

Eg	S/60 B	B/S	Ip (d.c.)
+ 9.0	37.1	1.616	35.5
+ 4.5	37.6	1.595	33.0
00	37.9	1.581	30.2
-4.5	38.2	1.569	28.0
- 9.0	38.8	1.546	25.5
-18	40.0	1.500	20.0
-27	39.5	--	9.2
-30	---	--	---

Plates get red at 60 milamperes Ip(d.c)

Ep = 300 volts

Eg = 0 "

I(f)=1.36 amps.

Ifil.	do	do	do
1.34	38.2	1.570	25.8
1.36	37.8	1.586	28.8
1.38	37.9	1.582	34.0
1.40	37.8	1.587	42.4
1.45	38.0	1.578	54.5

DATA -FREQUENCY VARIATION BY BEATS (340 CYC/SEC.)

Ep	S/60B.	B/S	Ip (d.c.)
300	31.5	1.904	37.1
270	32.0	1.875	35.0
240	32.9	1.825	31.7
210	33.7	1.780	28.0
180	34.8	1.725	24.9
150	35.8	1.675	21.5
120	37.7	1.592	18.0
90	39.7	1.511	12.7
60	----	-----	1.0

Variable Tube

L = 0.067 H.

C = 3.02 M.F.

f = 340+ c/s.

Standard Tube

L = 0.065 H.

C = 3.16 M.F.

f = 340 c/s.

Eg	do	do	do
- 40.5	---	---	----
- 30.0	35.0	1.714	29.5
- 15.0	34.6	1.735	26.2
0	31.9	1.882	33.2
+ 10.5	31.0	1.935	36.2
+ 20	30.2	1.986	42.9

Ep = 300 volt

Eg = 0 "

If = 1.36 A..

I (fila)	do	do	do
1.25	.32.3	1.856	27.2
1.30	32.2	1.862	30.8
1.35	32.4	1.852	34.0
1.40	32.4	1.852	46.0
1.45	32.6	1.840	57.0

DATA-FREQUENCY VARIATION BY BEATS (560 CYC/SEC.)

Ep	S/60B.	B/S.	Ip (d.c. milamps.)
300	33.2	1.796	34.0
270	33.2	1.806	31.4
240	32.4	1.852	28.8
210	31.9	1.879	26.2
180	29.8	2.01	23.0
150	28.6	2.10	20.2
120	24.5	2.44	17.0
90	21.4	2.80	13.5
60	18.8	3.19	8.3
45	19.3	3.11	5.4

Variable Tube

L = 0.067 H.

C = 1.24 M.F.

f = 560- c/s.

Standard Tube

L = 0.065 H.

C = 1.20 M.F.

f = 560+ c/s.

Eg	do	do	do
+ 20.5	30.0	2.00	35.5
+ 15	30.0	2.00	35.5
+ 10	30.0	2.00	35.0
+ 5	30.2	1.99	34.0
0	30.2	1.99	33.4
- 10	30.0	2.00	32.0
- 20	30.0	2.00	29.8
- 30	30.0	2.00	28.6
- 46	30.0	2.00	26.0

Ep = 300 volts.

Eg = 0 "

If = 1.36 amps.

I (fila.)	do	do	do
1.10	27.9	2.15	8.8
1.15	27.4	2.19	17.0
1.20	27.2	2.21	17.5
1.25	26.9	2.23	22.0
1.30	27.7	2.17	26.2
1.35	30.1	1.99	32.3
1.40	32.5	1.85	41.0

DATA-FREQUENCY VARIATION BY BEATS (864 CYC/SEC)

Ep	S/120B	B/S.	Ip (d.c.mila.)
300	23.8	5.04	24.0
270	26.5	4.53	22.0
240	32.7	3.67	19.9
210	38.4	3.13	17.6
180	53.4	2.25	15.5
150	83.2	1.44	12.4
	(unison at 130 volts)		
120	112.2	1.07	9.0
90	59.6	2.01	5.4
60	25.2	4.76	2.0
Eg	do	do	do
- 33	39.3	3.05	14.2
- 15	30.1	3.98	19.4
- 7.5	26.5	4.53	21.3
0	23.7	5.06	24.0
+ 7.5	23.9+	5.01	26.3
+ 15	22.4	5.36	29.0
+ 30	23.8	5.04	39.0
I(fila)	do	do	do
1.25	23.4	5.12	16.0
1.30	21.7	5.53	19.2
1.35	24.0	5.00	23.2
1.40	33.4	3.59	28.0
1.46	unison	.00	35.6

Variable Tube

L = 0.067 H.

C = 0.487 M.F.

f = 880- c/s.

Standard Tube

L = 0.065 H.

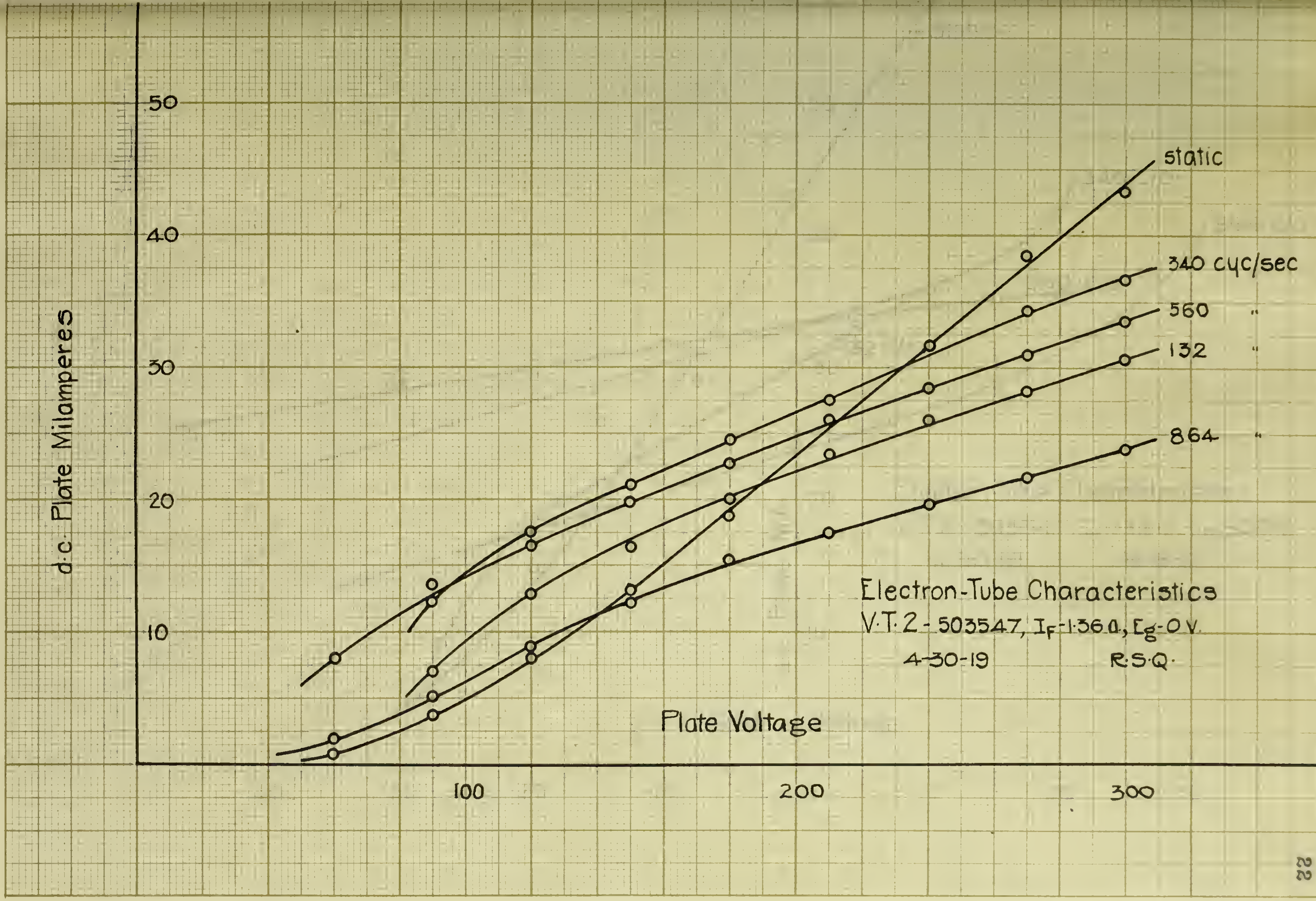
C = 0.445 M.F

f = 860+ c/s.

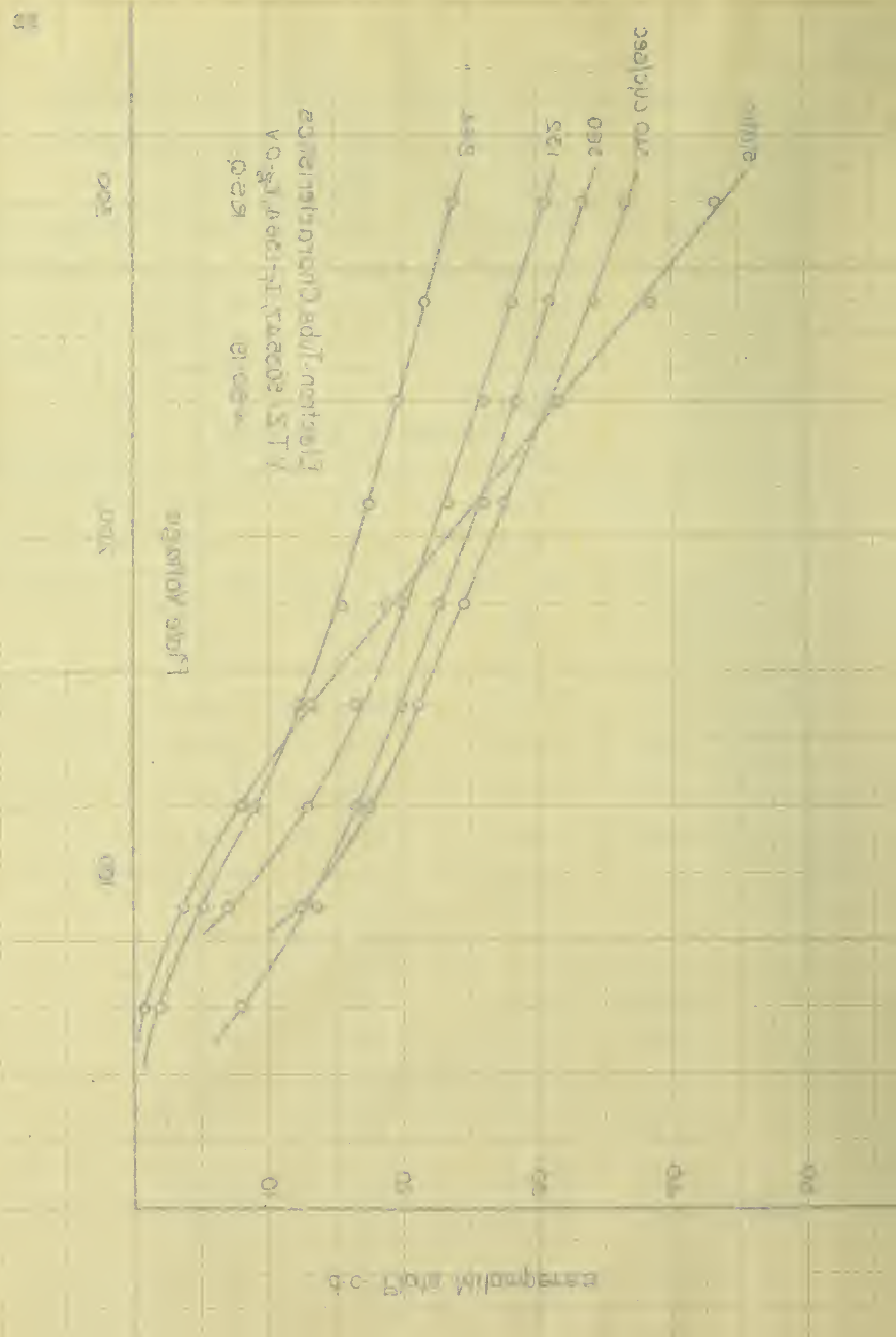
Ep = 300 V.

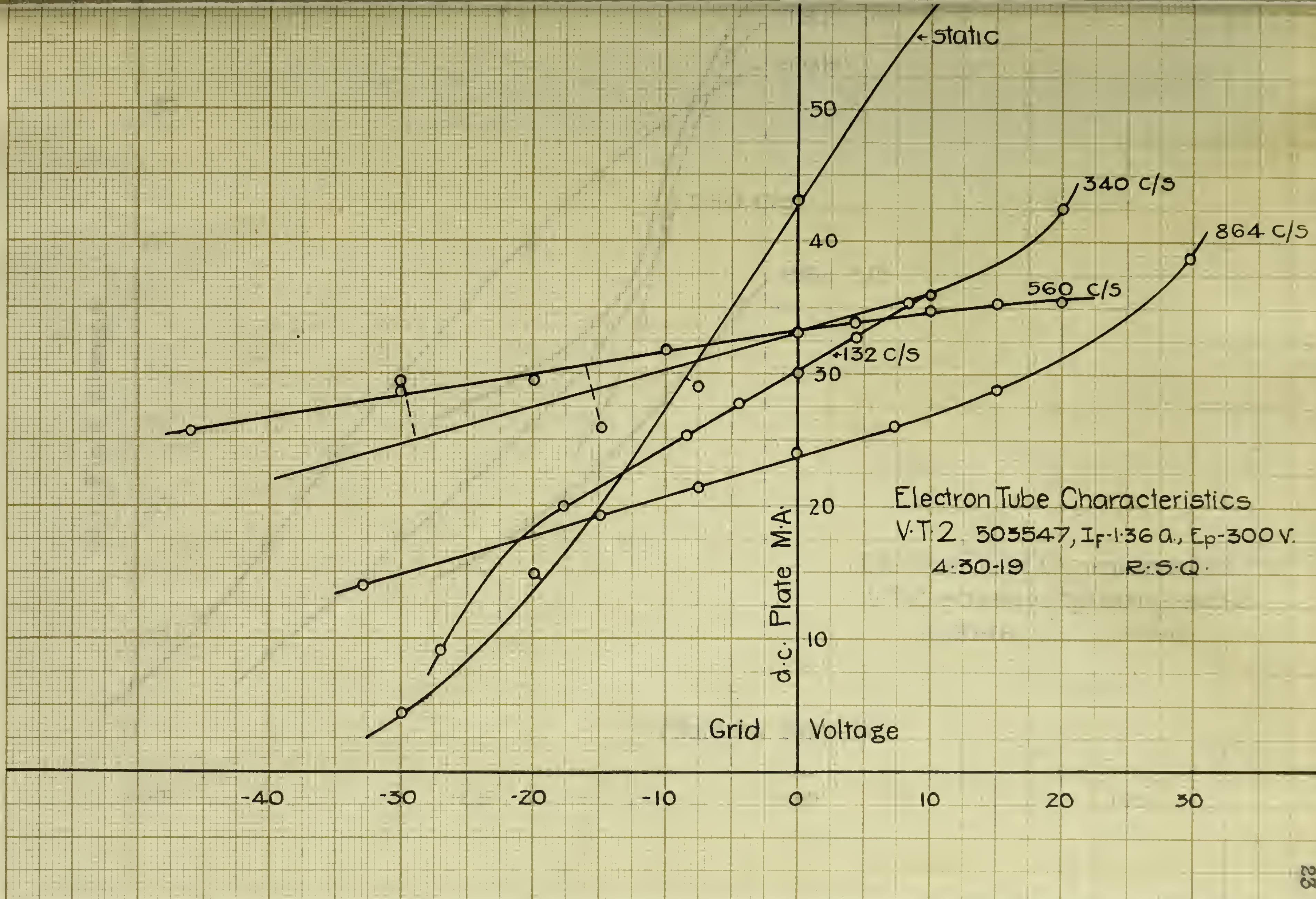
Eg = 0 "

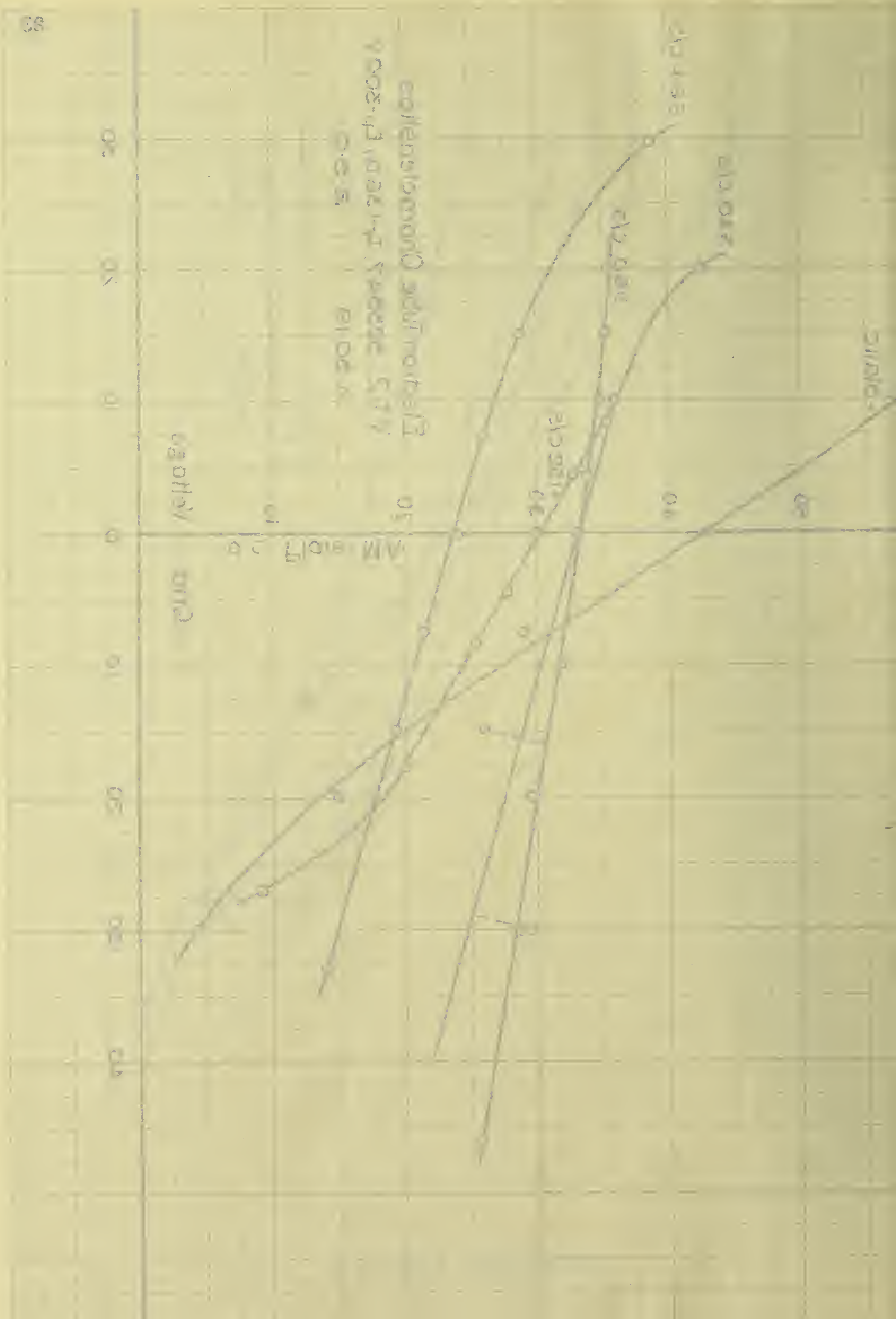
I (fil) = 1.36 A.

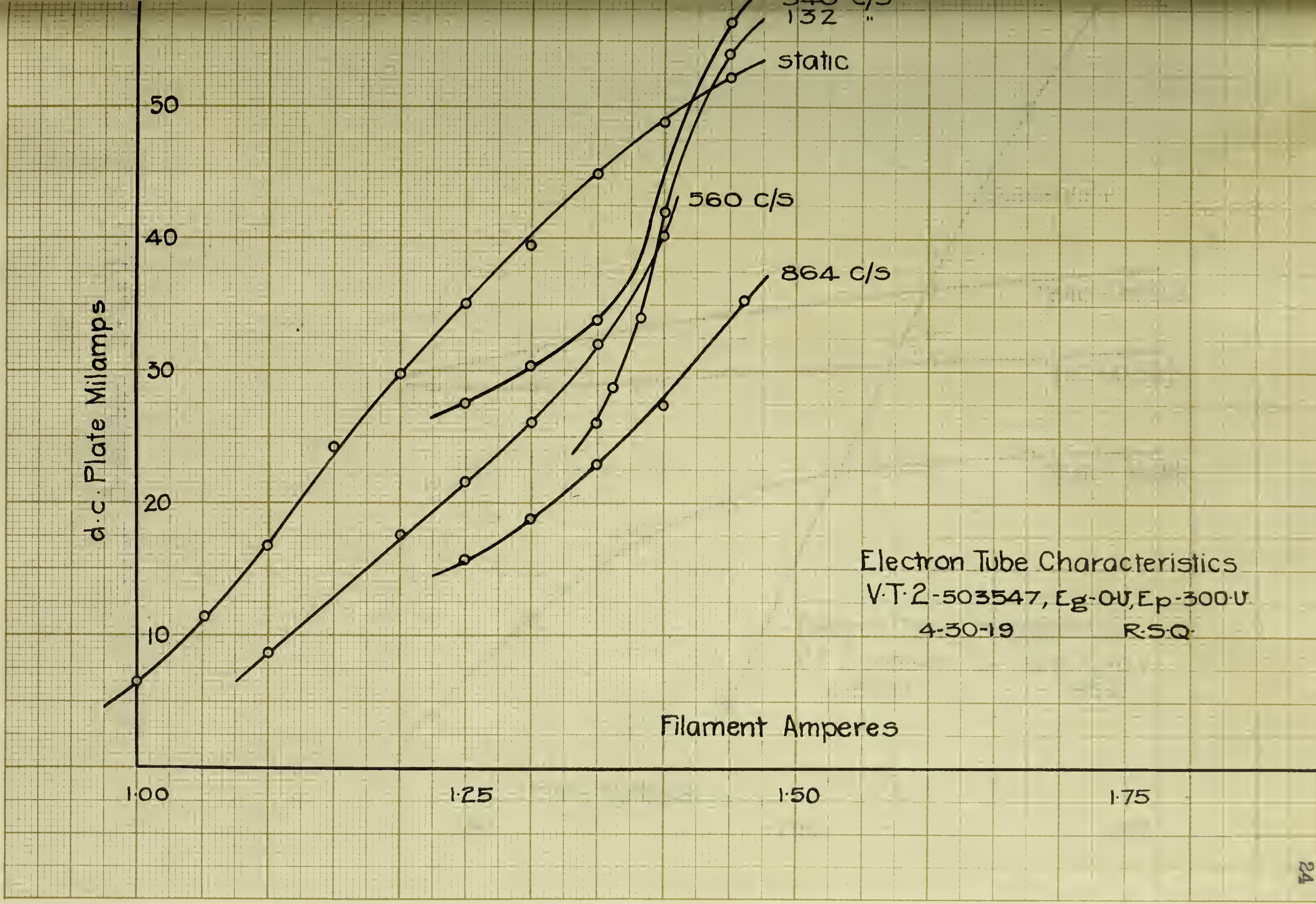


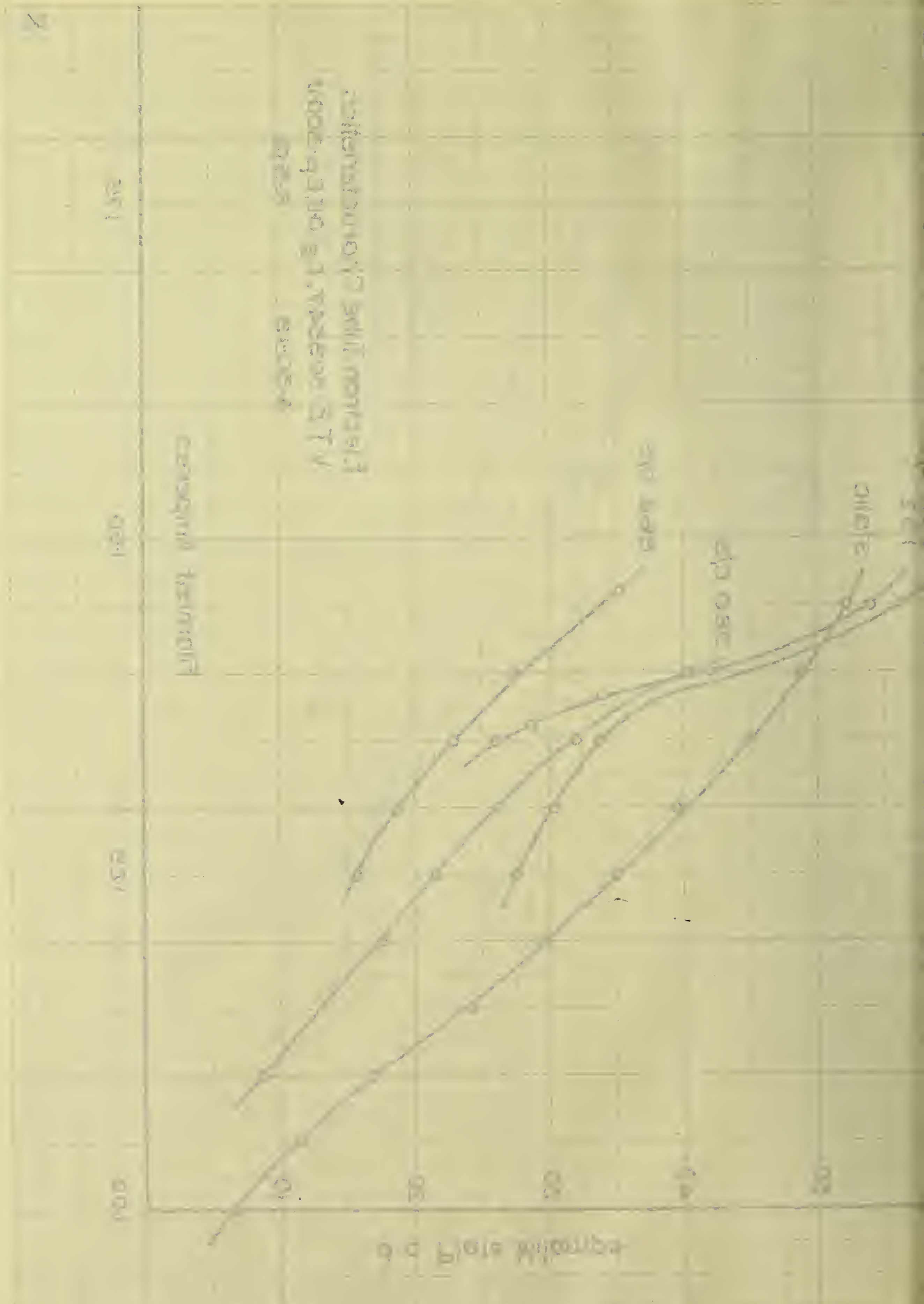
static
340 cyc/sec
560 "
132 "
864 "
50
40
30
20
10
100
200
300
d.c. Plate Milamperes
Plate Voltage
Electron-Tube Characteristics
V.T.2 - 503547, I_F-1.36 a, E_g-0 V.
4-30-19
R.S.Q.

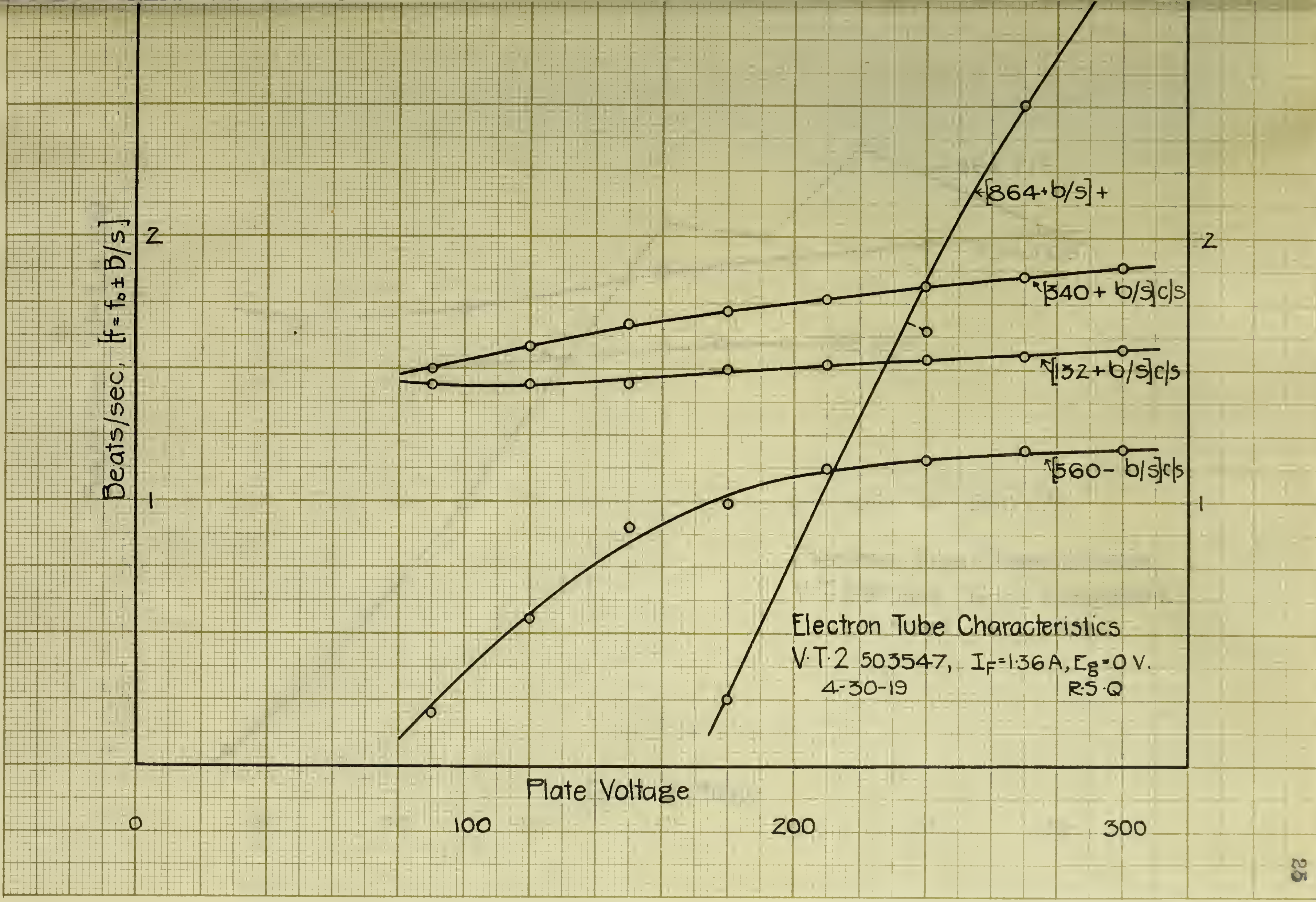



Electron Tube Characteristics
V·T·2 503547, I_f-1·36 a., E_p-300 V.
4·30-19 R·S·Q·
static
340 c/s
864 c/s
560 c/s
132 c/s
d.c. Plate M·A·
Grid Voltage
50
40
30
20
10
-40
-30
-20
-10
0
10
20
30

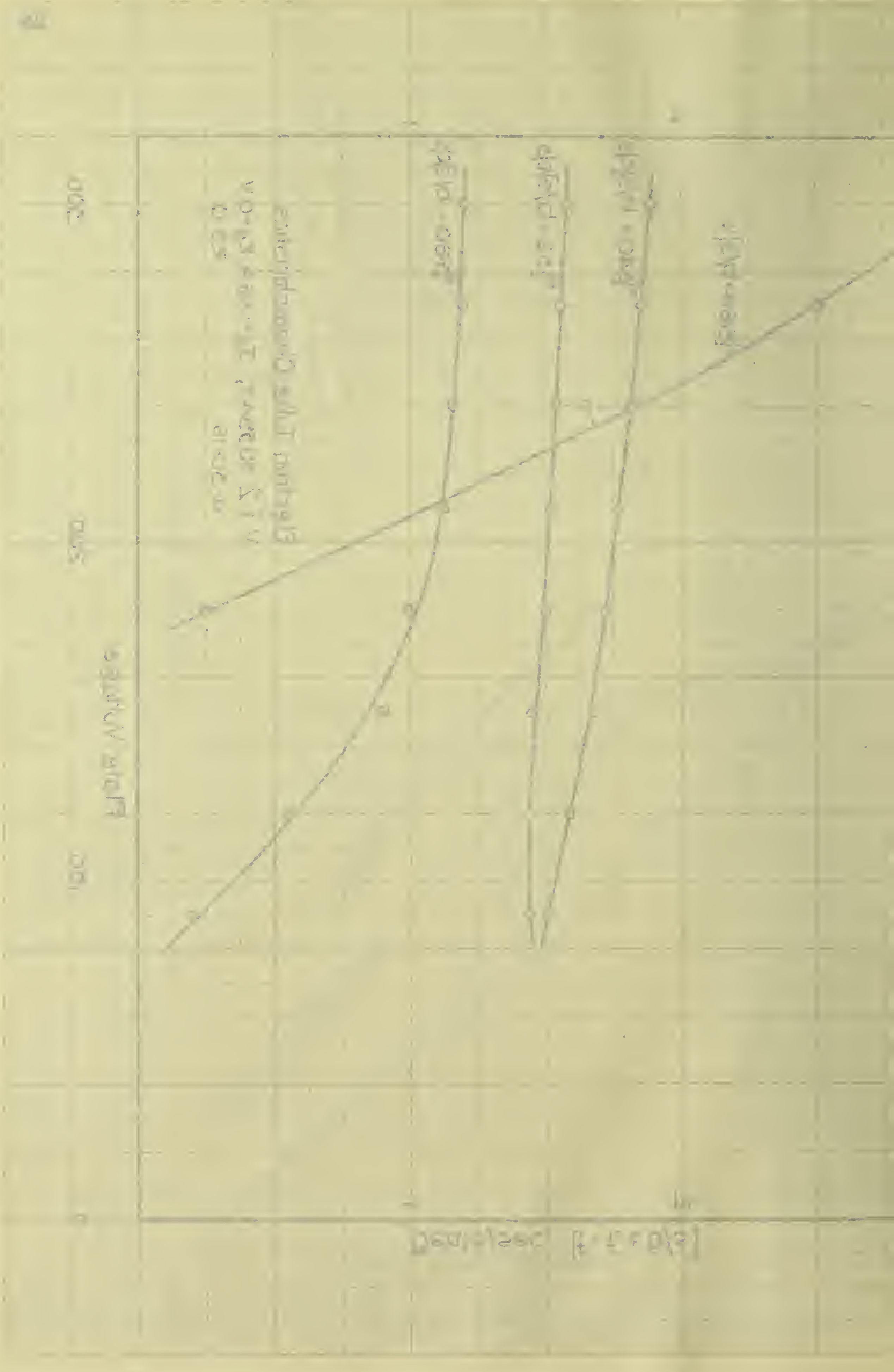


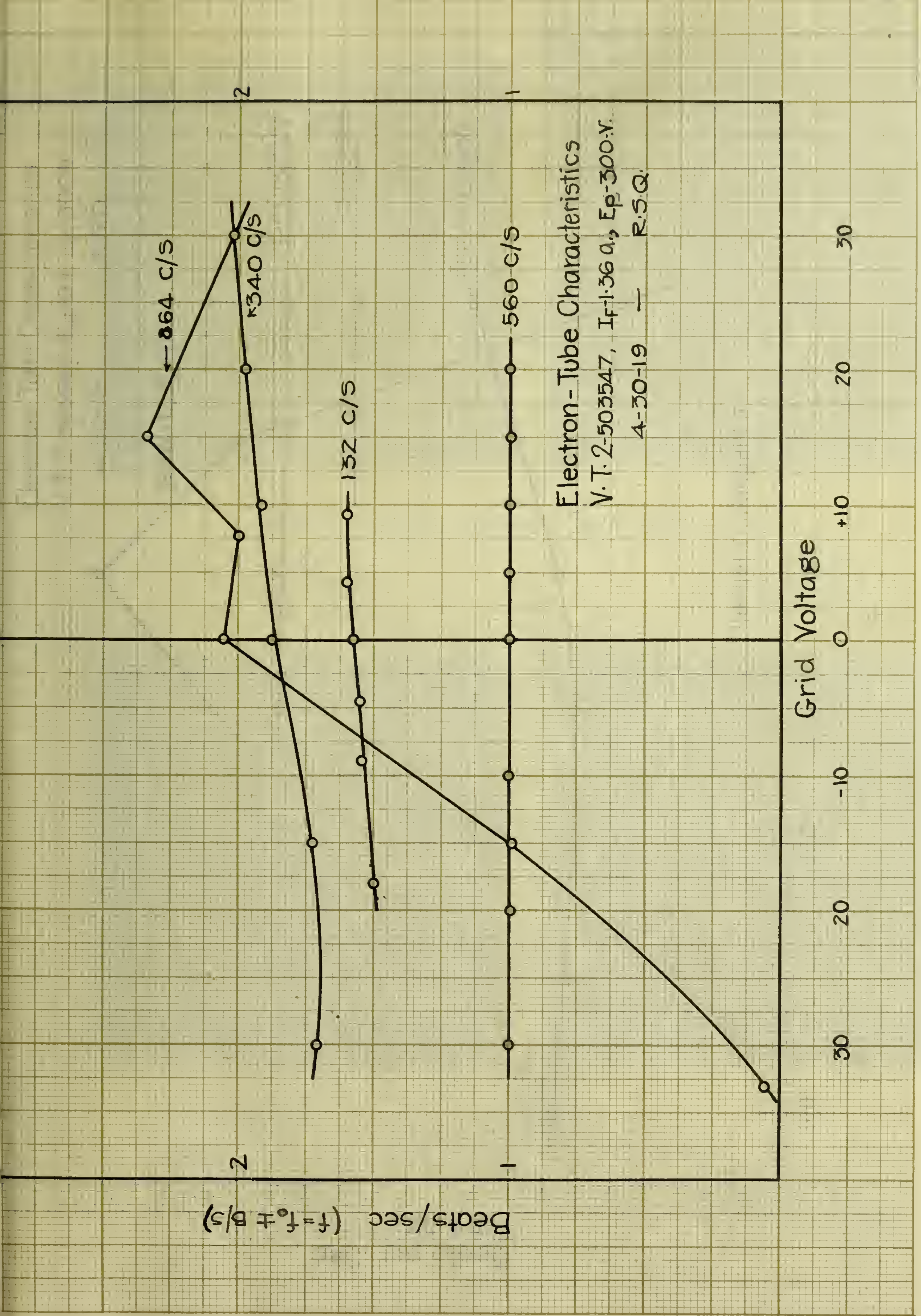

132 "
static
560 c/s
864 c/s
50
40
30
20
10
d.c. Plate Milamps
1·00
1·25
1·50
1·75
Filament Amperes
Electron Tube Characteristics
V·T·2-503547, Eg-0U, Ep-300U
4-30-19
R·S·Q·

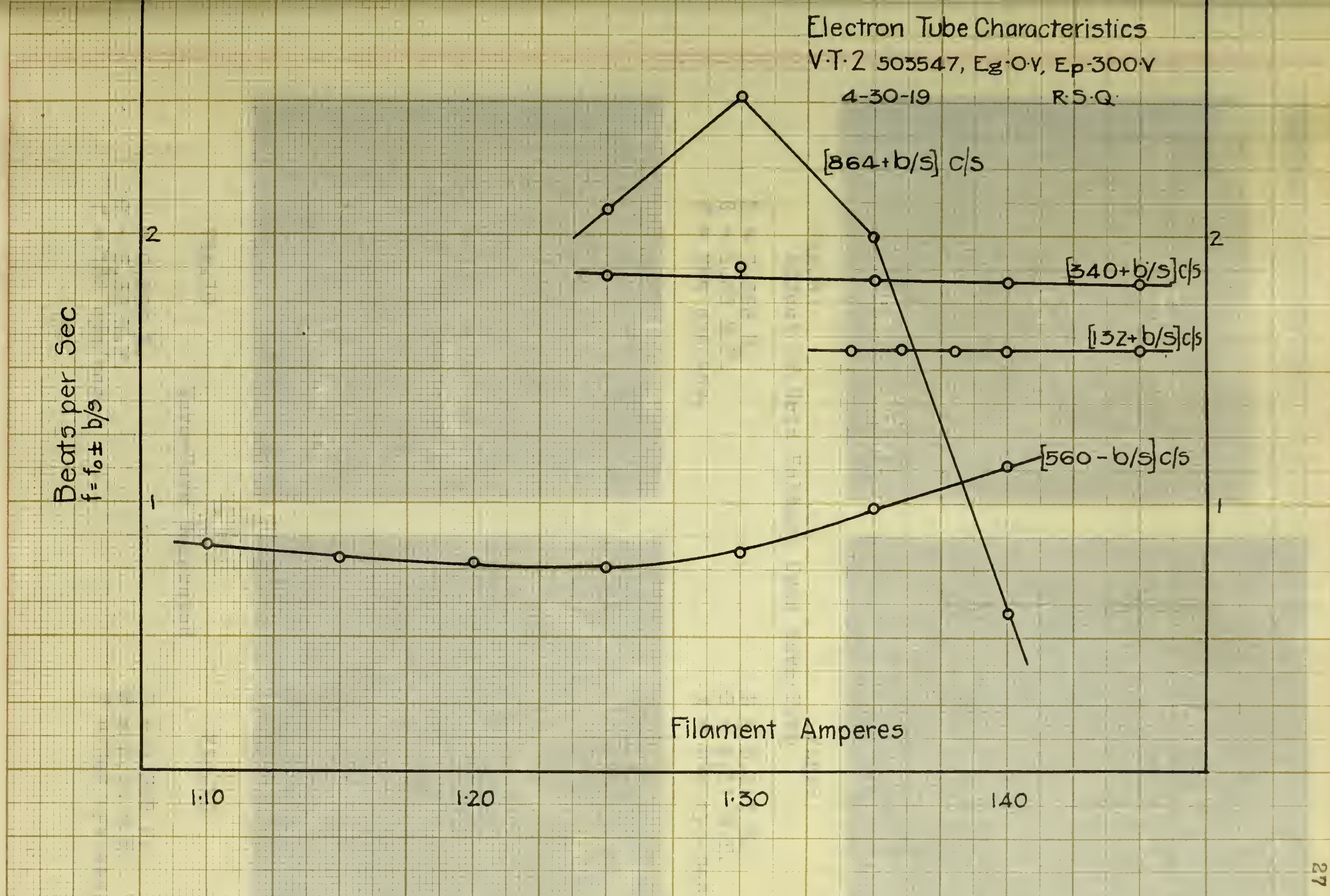


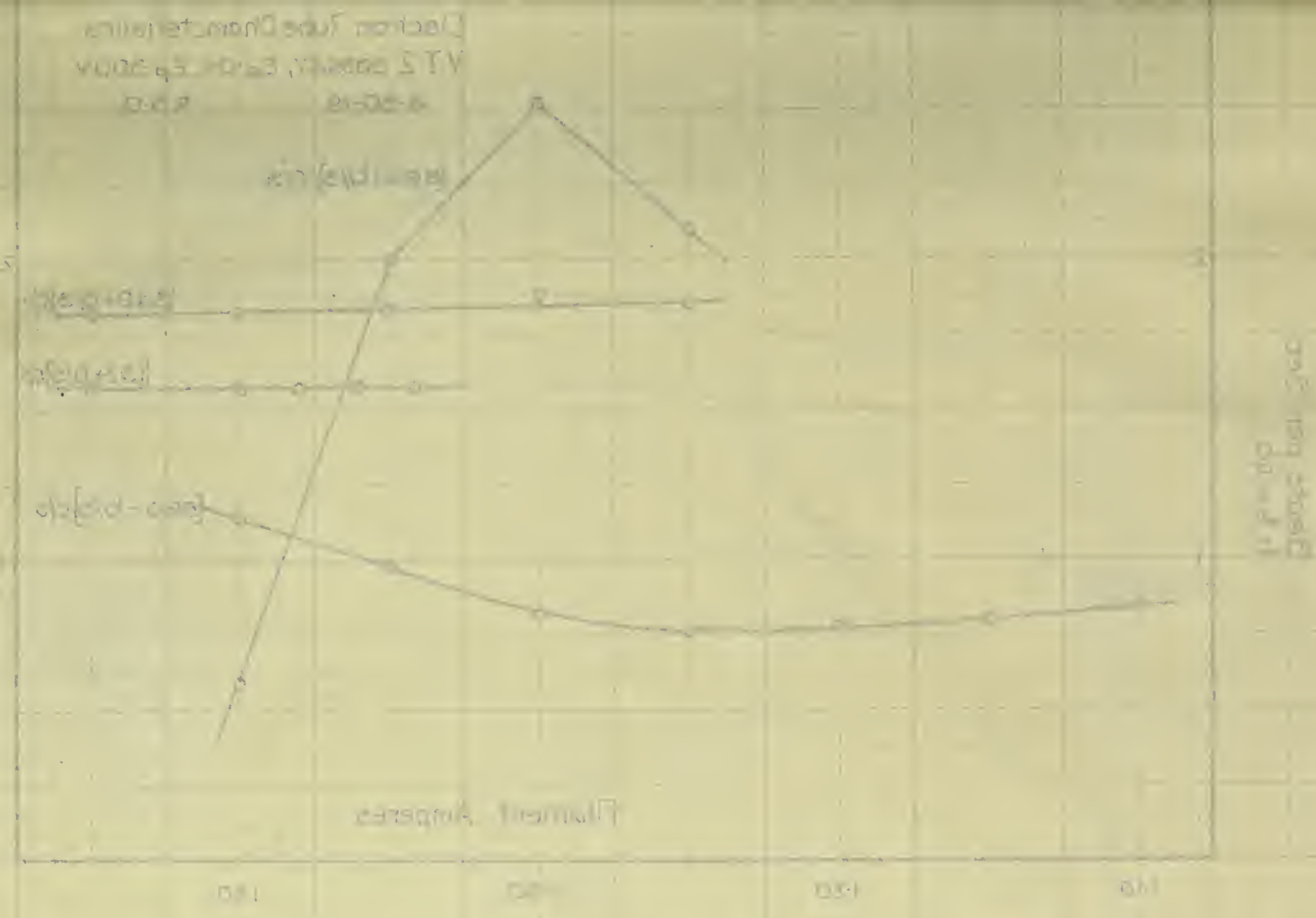


[864+b/s]+
[340+b/s]c/s
[132+b/s]c/s
[560- b/s]c/s
Beats/sec, [f=f₀±B/s]
2
1
0
100
200
300
Plate Voltage
Electron Tube Characteristics
V·T·2 503547, I_F=1·36 A, E_g=0 V.
4-30-19
R·S·Q

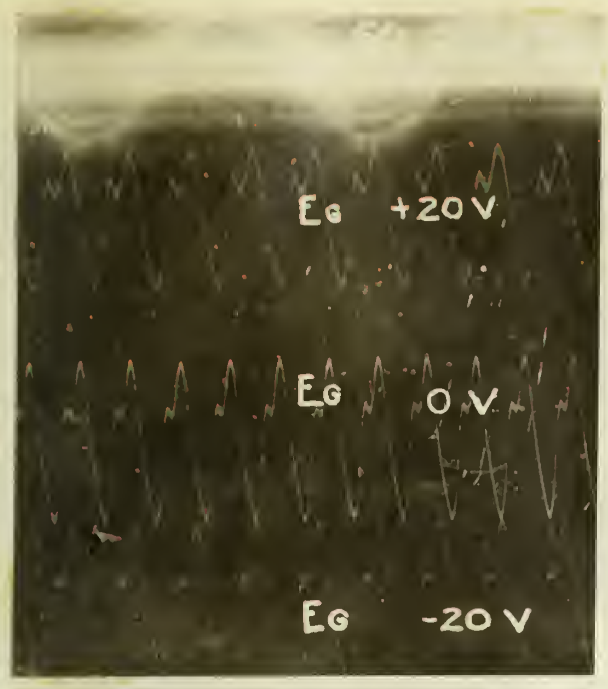



Electron-Tube Characteristics
V.T. 2-503547, I_f-1.36 a., E_p-300 V.
4-30-19 — R.S.Q.
864 C/S
340 C/S
132 C/S
560 C/S
Grid Voltage
30
20
-10
0
+10
20
30
1
2
Beats/sec ($f = f_0 \pm B/S$)


Electron Tube Characteristics
V·T·2 503547, Eg·0·V, Ep·300·V
4-30-19
R·S·Q·
[864+b/s] c/s
[340+b/s] c/s
[132+b/s] c/s
[560-b/s] c/s
Beats per Sec
f = f0 ± b/s
Filament Amperes
1·10
1·20
1·30
1·40
1
2



Electron Tube Characteristics
Filament Amperes



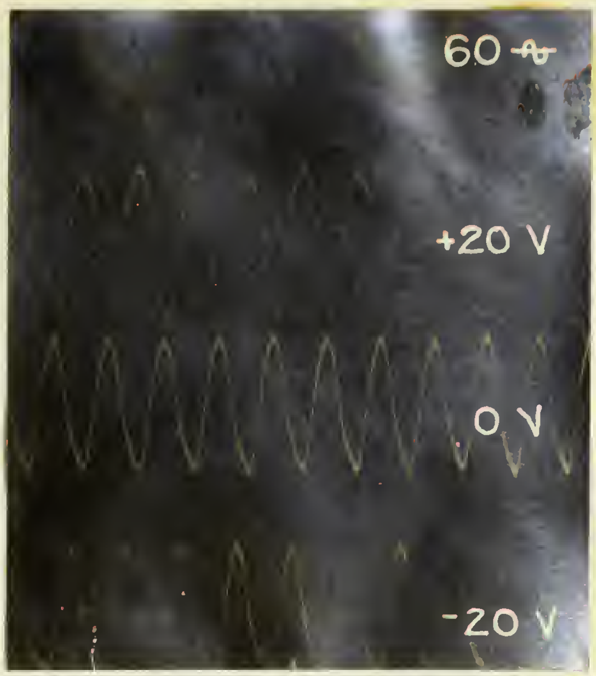
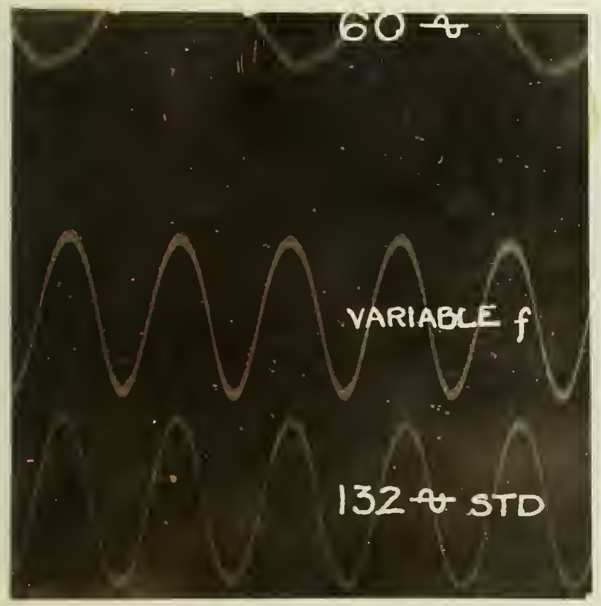


Fig. 8 Fig. 9

Effect of Grid Voltage Upon Wave-Form

L = 0.268 H.
C = 1.09 M.F.
f = 284 cyc/sec.

L = 0.067 H.
C = 4.11 M.F.
f = 296 cyc/sec.



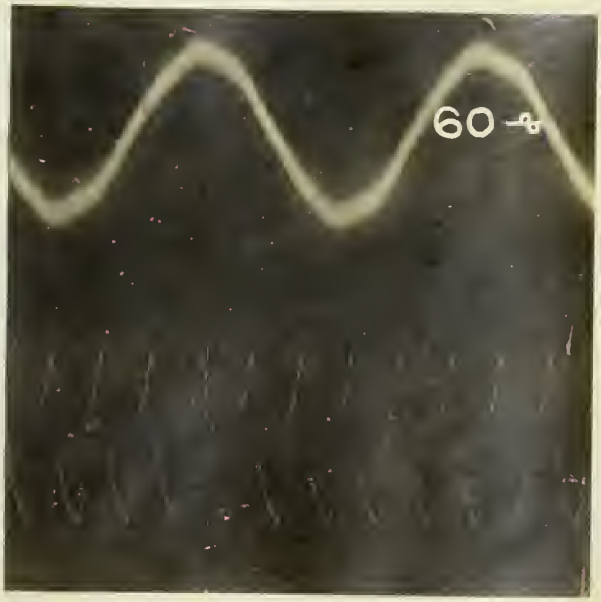


Fig. 10 Fig. 11

Wave-Form Generated

L = 0.268 H.
C = 5.32 M.F.
f = 132 cyc/sec.

L = 0.065 H.
C = 3.16 M.F.
f = 340 cyc/sec.

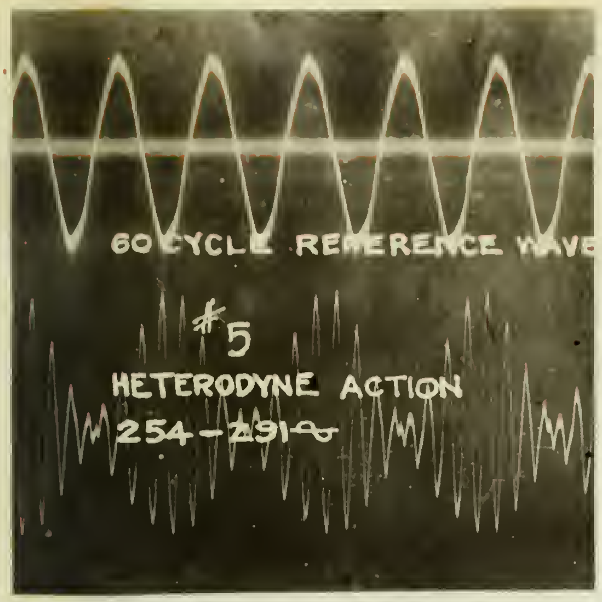


Fig.12
Measurement of frequency by Beats.

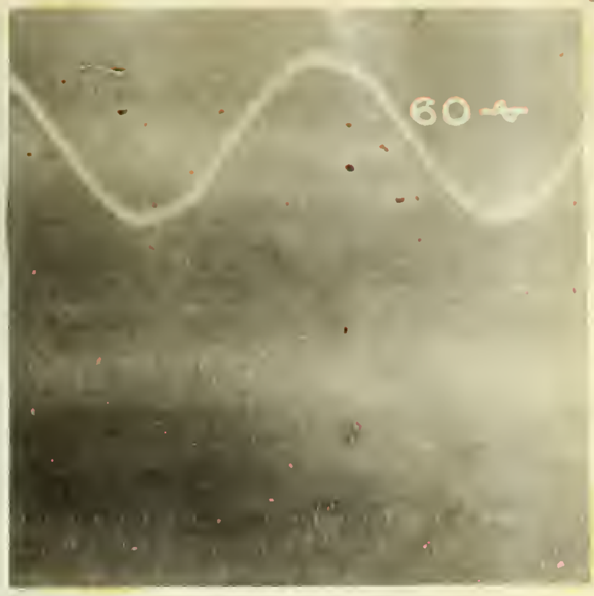


Fig.13
Wave-Form Generated.

L = 0.065 H.
C = 0.445 M.F.
f = 864 cyc/sec.

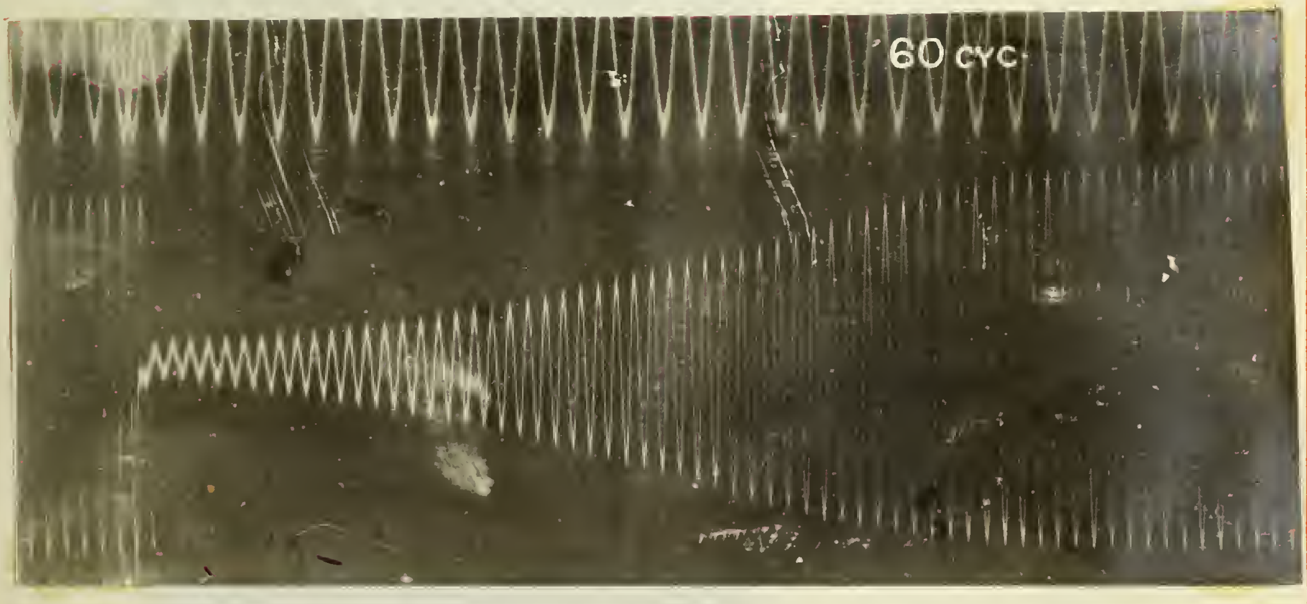


Fig.14

Transient of a Sustained Oscillation.

L = 0.268 H.
C = 5.35 M.F.
f = 132 cyc/sec.

Fig. 15

Heterodyne Action Showing Beat Pattern Produced by Two Distorted Wave-Forms.

f = 540 Cycles/second.

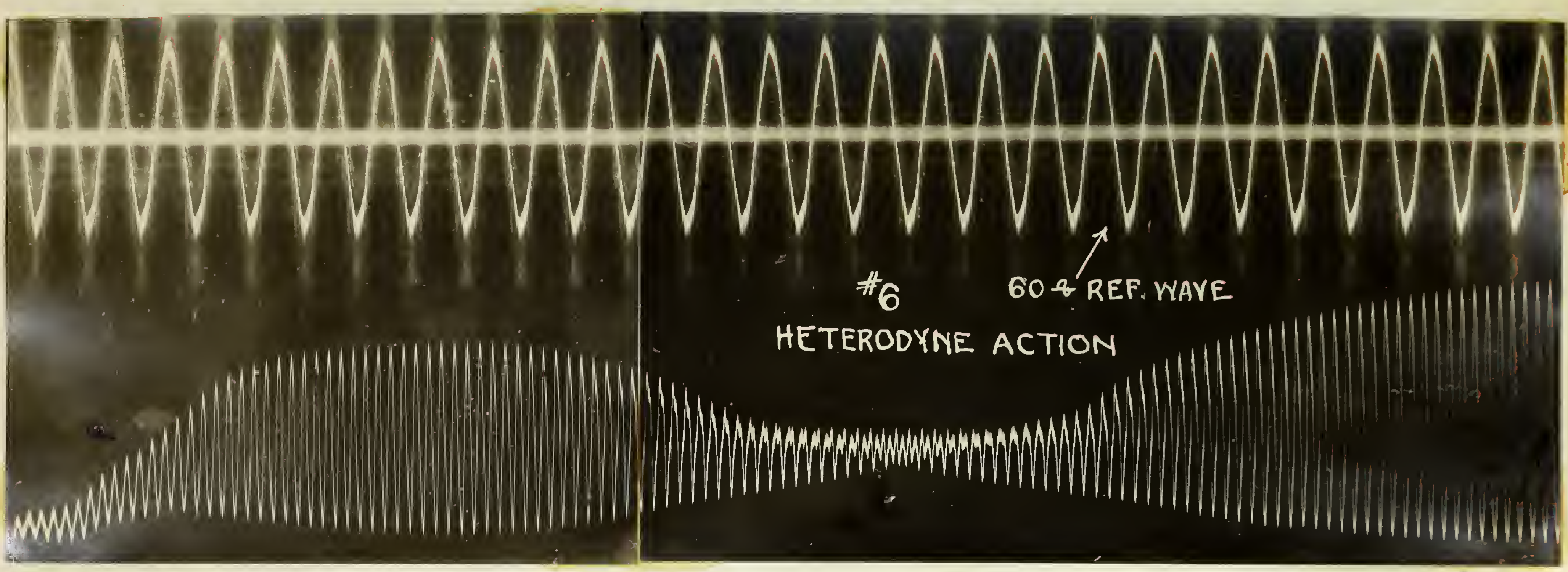


Fig. 16

Starting Transient of Heterodyne Action

f = 290 Cycles/second.

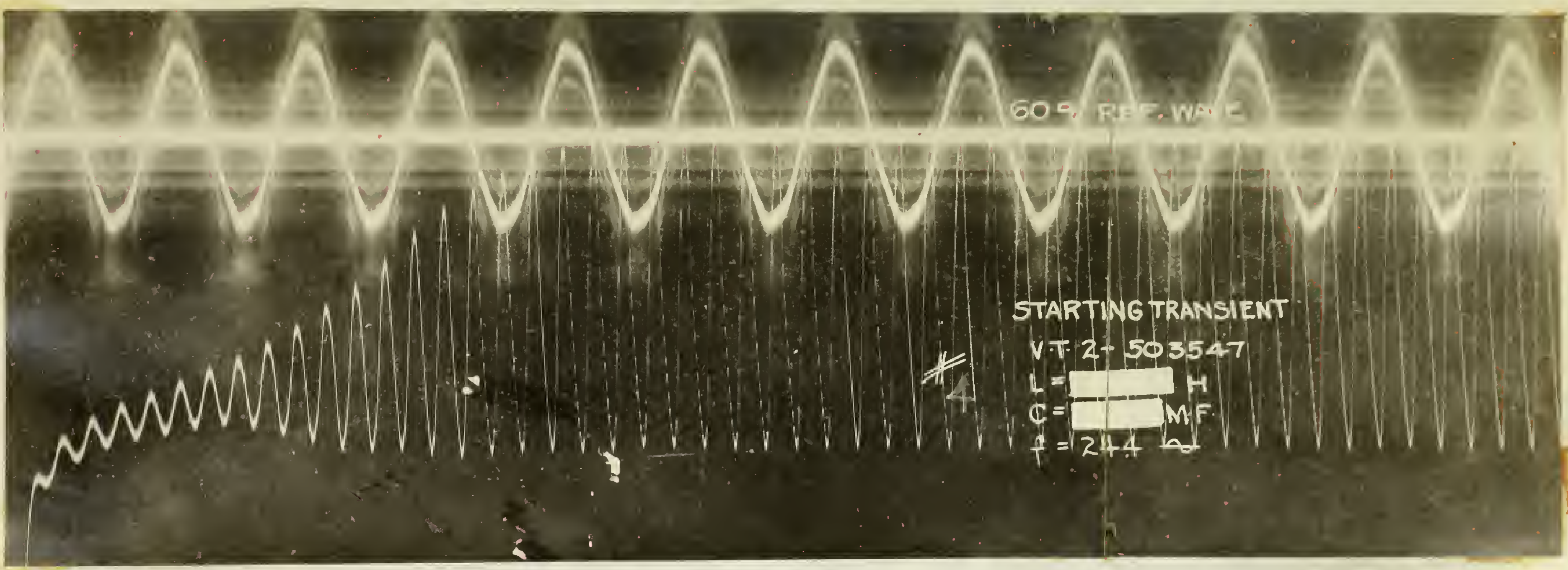


Fig. 17

Starting Transient of an Unstable Oscillation

L = 0.067 H.
C = 7.06 M.F.
f = 264 cyc/sec.

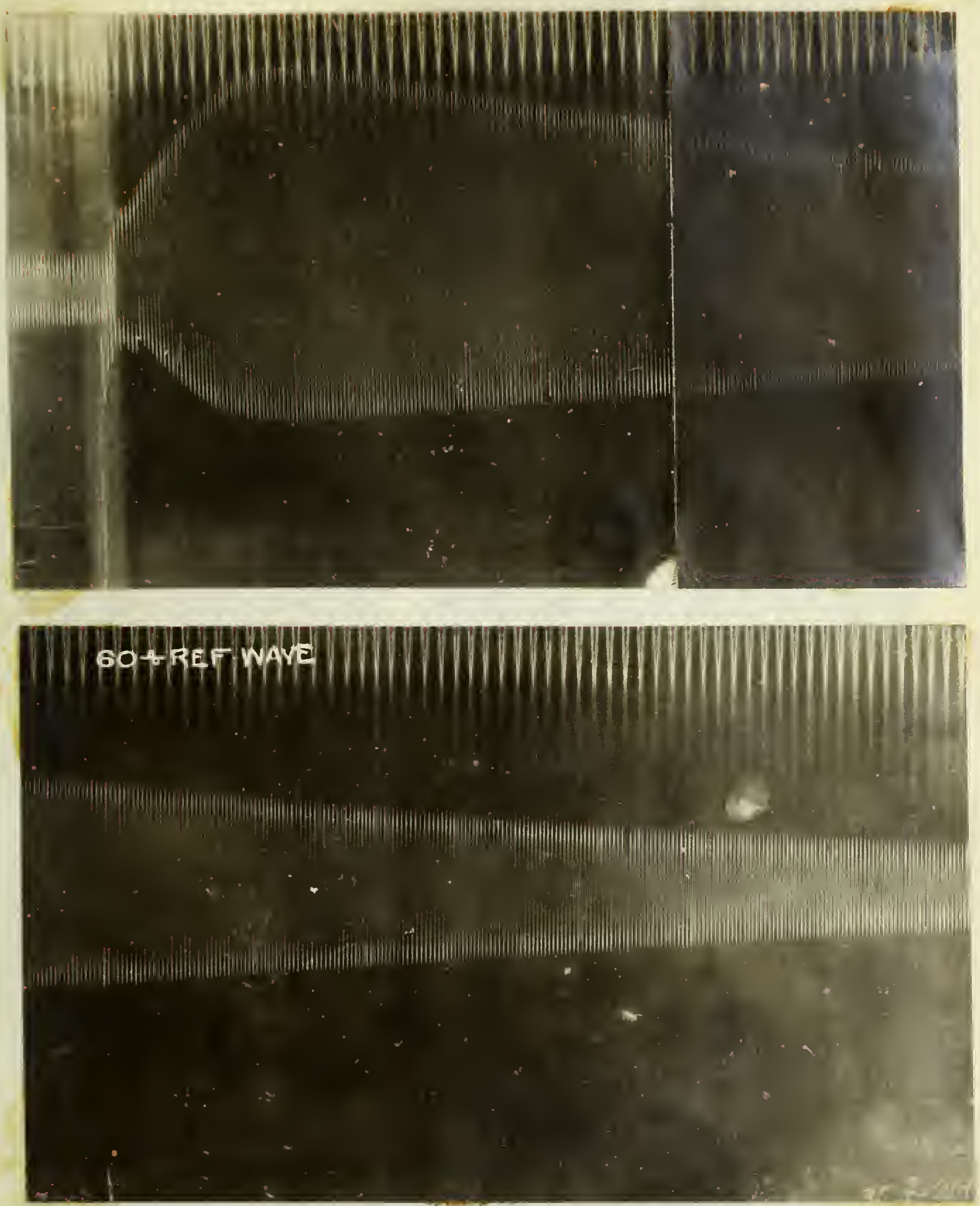


Fig. 18

Starting Transient of an Unstable Oscillation

$L = 0.067$ H.

$C = 7.06$ M.F.

$f = 219$ cyc/sec.

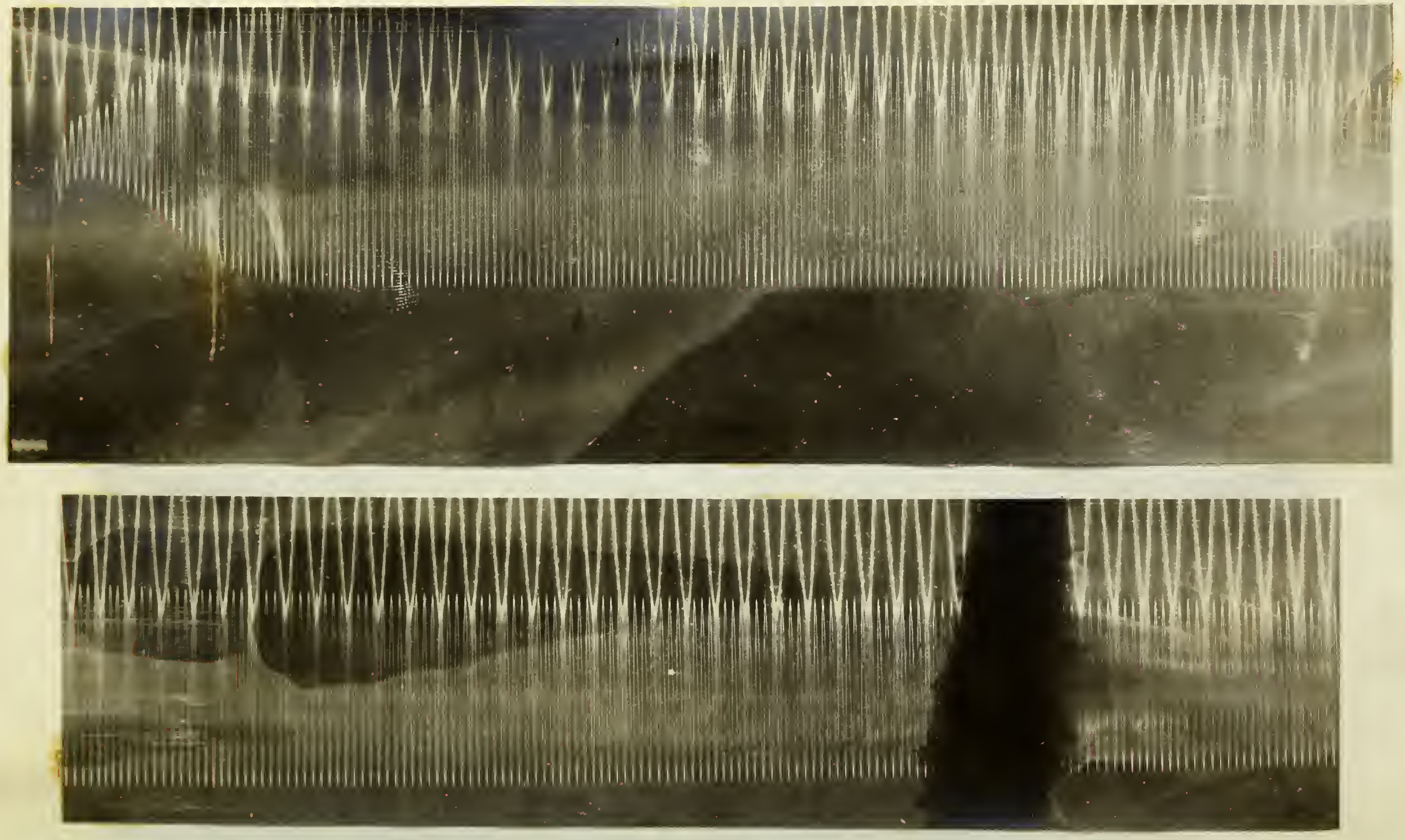


Fig. 19a

Starting Transient of an Unstable Oscillation

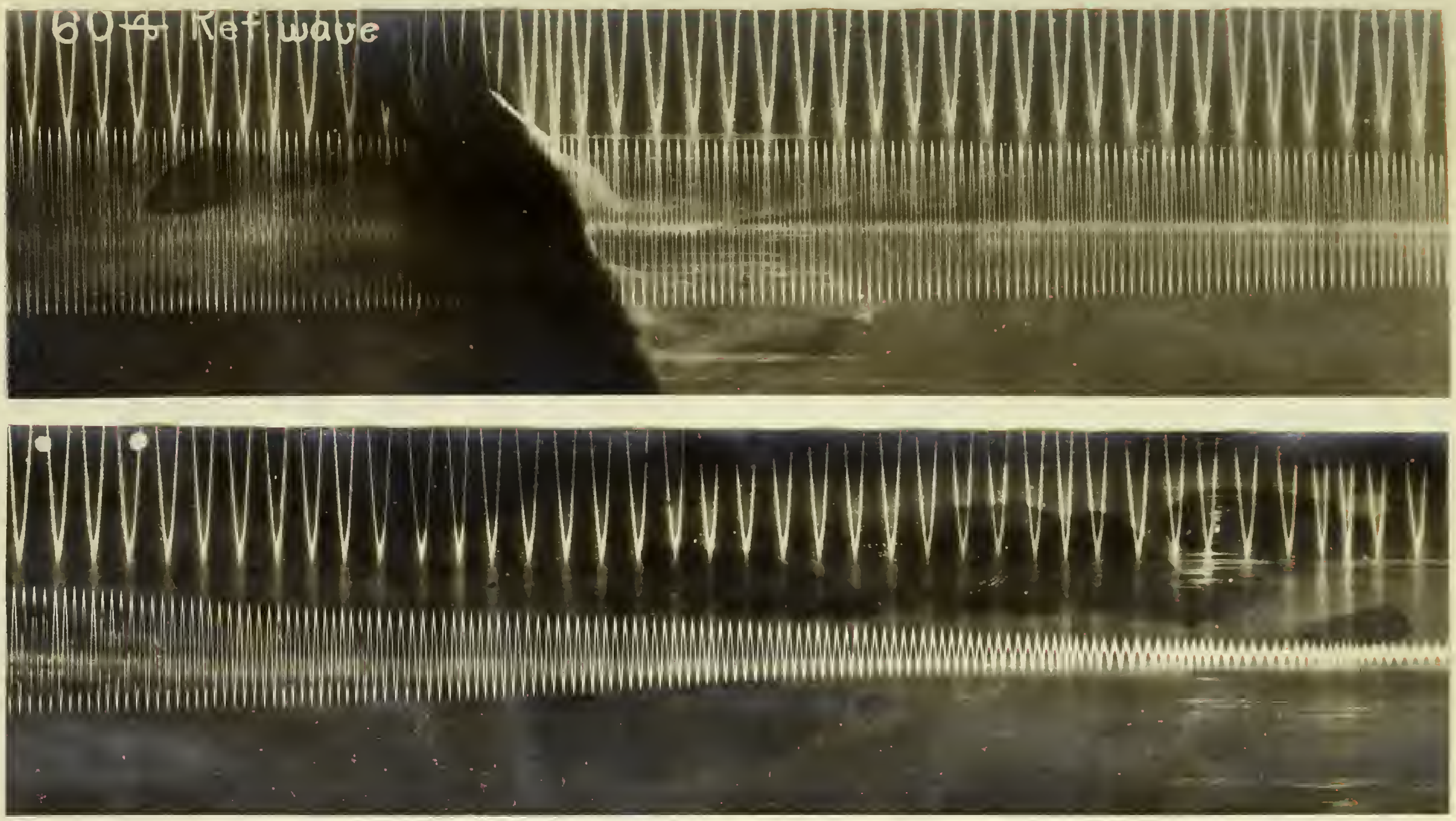


Fig. 19c.

Starting Transient of an Unstable Oscillation.

$L = 0.067$ H.
$C = 7.06$ M.F.
$f = 226$ cyc/sec.

IV DATA AND EXPERIMENTAL RESULTS

1. Observed conditions necessary for constant current and for oscillating current. Oscillations always occur with any values of inductance and capacity providing the coupling be sufficiently large. The necessary minimum coupling, expressed in terms of mutual inductance, as given by calculation from the expression

is as follows:

$$M = -\frac{K_2L+(1+K_2R_1)RC}{K_1}$$

Theoretically, if the required coupling be less than that expressed, no oscillations will persist. A study of the above results shows that in three cases the experimental coupling is less than the calculated and yet oscillations did persist. This discrepancy is no doubt due to wrong assumptions in the derivation of the expression for the required coupling. Grid current has been neglected and the operating surface has been assumed as plane. Either or both of these assumptions should be studied again and justified if they are allowable.

2. Oscillograms. Starting transients of oscillations have been shown in prints on pages 28-35, incl. Inspection of these oscillograms show that they consist of two parts; a transient of the direct current component and one of the alternating current component.

Two classes of oscillations were apparent: stable and unstable. The former class would persist indefinitely while the latter would last only for a few seconds. The unstable transients could not be repeated in rapid succession by opening and closing the plate circuit switch. An interval of at least thirty seconds was necessary to let the tube recuperate to its original state. Attempts to produce oscillations at intervals of only a few seconds resulted in only the d.c. component appearing. Whether this condition was due to gas in the tube or to a critical value of coupling is not known at present.

The wave-form generated is most effected by the ratio L:C and not by the grid potential. This is shown by the prints on page 28-figs.8,9. In the first the wave-form is highly distorted with a ratio L:C of 0.246. When the ratio is changed to 0.163 the wave-form is much less distorted(2). At a frequency of 132 cyc/sec. the wave is a very good sine. The ratio is 0.050. (Henries :Microf.) The conclusion that can be drawn from the above is that the wave-form is corrected by changing the ratio L:C and not by changing the grid potential.

The limits of frequency for the above method of studying frequency variation are those in which the beats remain within a counting range while operating conditions are varied. The experimental limits encountered were those imposed by the constants of the circuit set-up used. The observed range was from 132 to 864 cycles per second.

3.Experimental results. All experimental results have been shown graphically. Frequencies used were 0 (static),132,340,

560,and 864 cycles per second.The current measured in each case was the d.c.component of the plate circuit current.Examination of the curves shows that the Ip-Ep characteristics vary with the frequency.The characteristics for the oscillating family are different in form to that of the static. Since K_2 is given by the slope of the characteristic it follows that it is a variable and not independent of the frequency as has been concluded by other investigators (18). The Ip-Eg characteristics also vary in a like manner so it follows that K_1 is dependent upon the frequency.

Since the electronic emission increases with the temperature of the filament it would be expected that the current would vary with the filament current.This proved to be the case.

The frequency shows a decrease with a decrease of plate potential.This decrease at 132 cycles is 0.06 cyc/sec. (0.045 %) for a change from 300 to 200 volts,plate potential. At 864 cyc/sec, for a like change of potential,the change in frequency is 2.3 cyc/sec. (0.27%). Intermediate frequencies show variations within the above range.

Changes in grid potential and in filament current produce no consistent nor appreciable change in frequency. This is in agreement with theoretical considerations even when grid current is considered.

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(18).Theory of the Thermionic Amplifier. H.J.van der Bijl. Proc. I.R.E. Apr.1919. Phy. Rev. Sept. 1918.

A Dynamic Method for the Determination of the Characteristics of Three-electrode Vacuum Tubes. J.M.Miller. Proc. I.R.E. June,1918.

CALCULATED ELECTRON-TUBE CHARACTERISTICS ---(V.T. #2 503547)

$$f_o = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}\ ,\quad f = f_o\sqrt{1 + K_2R} = f_oF$$

$$Ip(d.c.) = \frac{K_2E}{1 + K_2R} = K_2E \qquad (K_2R = 0,\text{approx.})$$

$$M\ (H.) = -\ \frac{CR(1 + K_2R_1) + K_2L}{K_1} = -\ \frac{CR + K_2L}{K_1}\ , \qquad (R_1=0)$$

$10^4 \times K_2$

Ep	0	132	340	560	864
300	2.05	0.85	0.92	0.85	0.71
250	"	"	1.05	"	"
200	"	0.90	"	0.80	0.72
150	1.85	1.20	"	1.00	0.95
100	1.35	2.00	1.82	1.30	1.33

K_2E

Ep	0	132	340	560	864
300	61.5	25.5	27.6	25.5	21.3
250	51.2	21.3	26.3	21.3	17.7
200	41.0	18.0	21.0	16.0	14.4
150	27.8	18.0	15.7	15.0	14.2
100	13.5	20.0	18.2	13.0	13.3

M (henries)

"f" c/s,	L-(H),	C-m.f.,	R-(0).,	$K_2 \times 10^4$,	$K_1 \times 10^4$,	M-(calc),	M-(act),	Osc.
132	0.268	5.35	13.1	0.85	6.0	0.154	0.147	St-dy.
244	0.067	7.06	6.6	1.10	3.7	0.144	0.07	Trans.
340	"	3.02	"	0.92	2.7	0.097	"	St-dy.
560	"	1.24	"	0.85	1.6	0.087	"	"
864	"	0.487	"	0.71	3.0	0.026	"	"

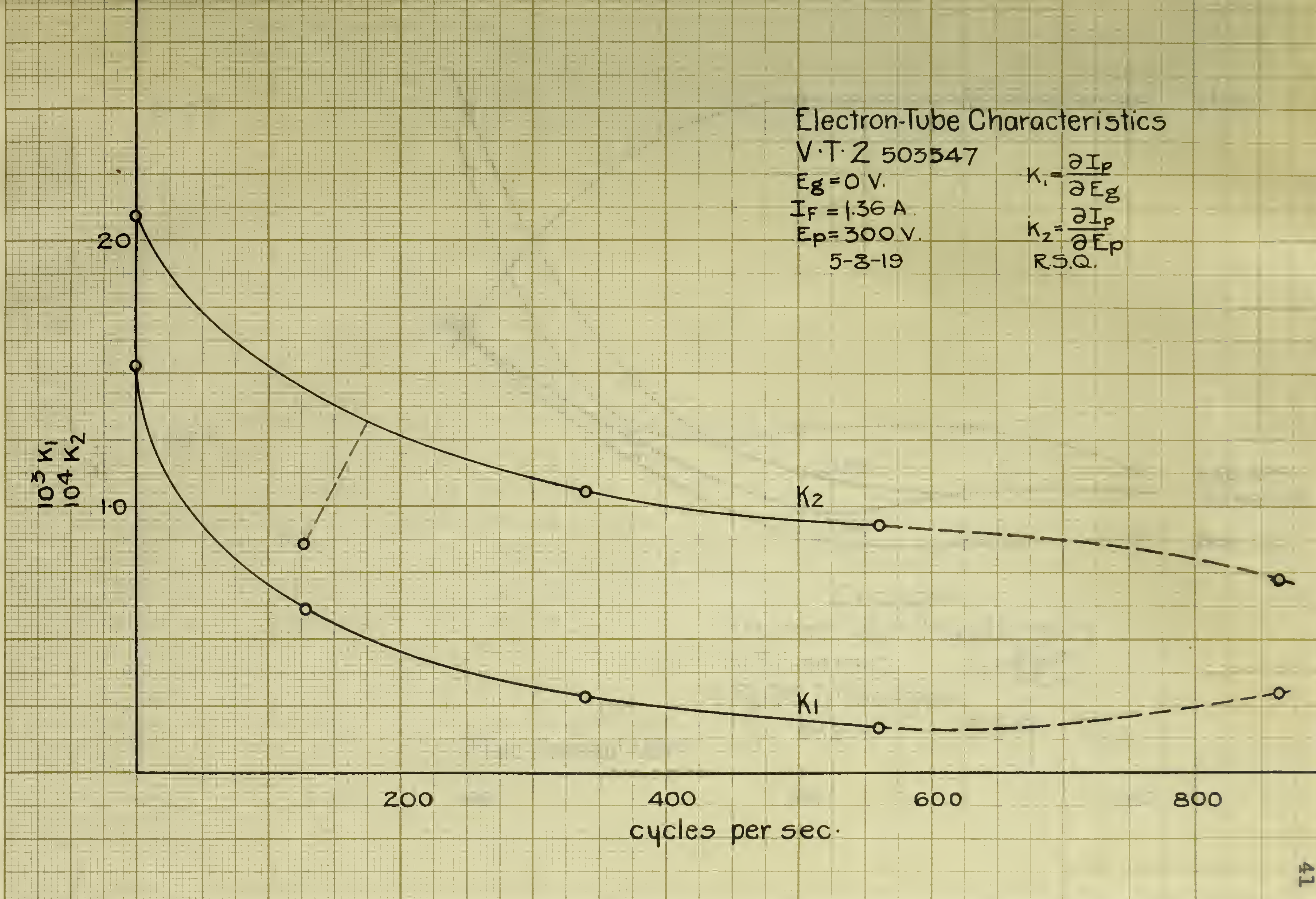
CALCULATED ELECTRON-TUBE CHARACTERISTICS (CONT'D)

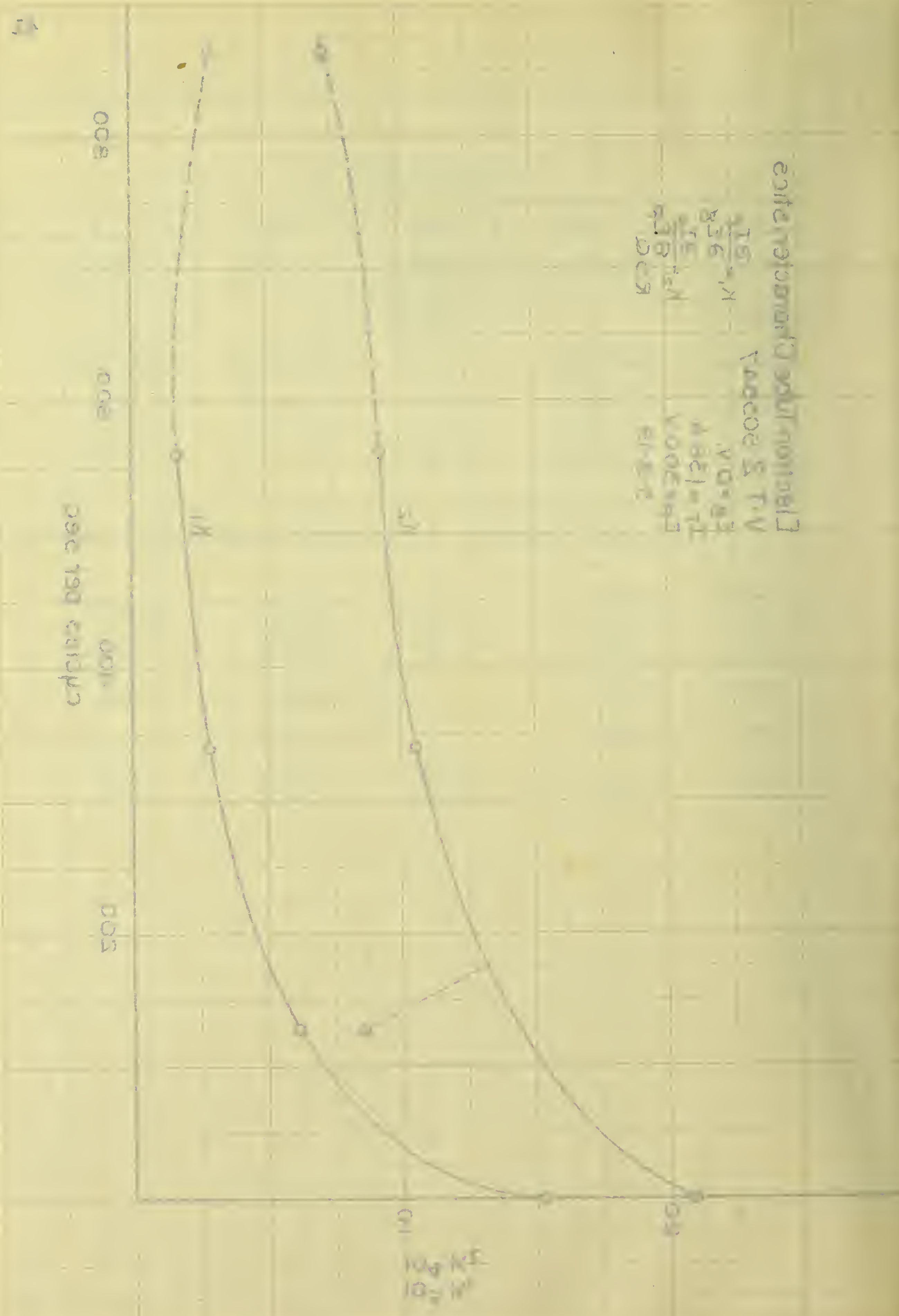
$\sqrt{1 + K_2R}$

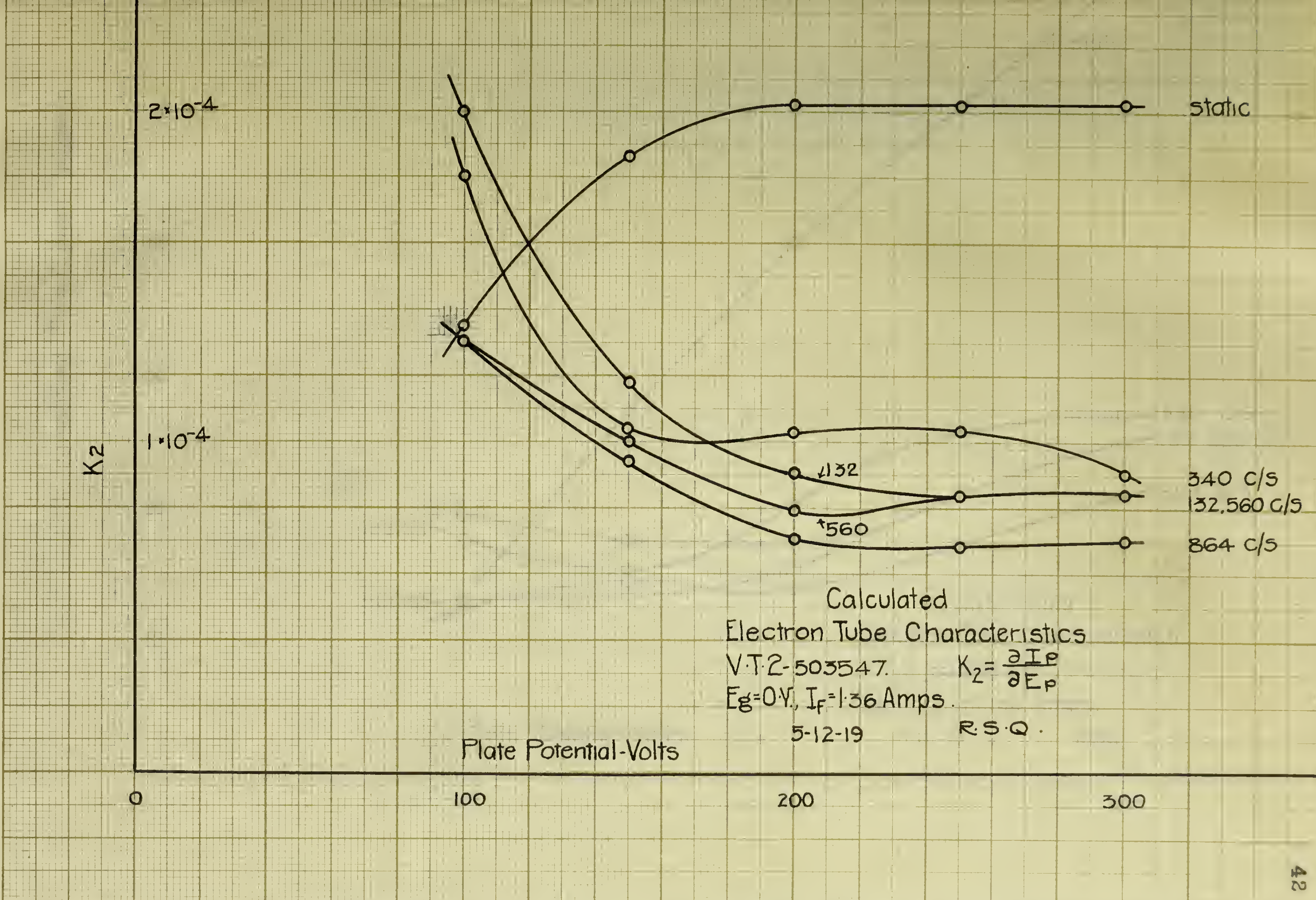
Ep	132	340	560	864 (cyc /sec)
300	1.00056	1.00030	1.00028	1.00023
250	"	1.00039	"	"
200	1.00060	1. "	1.00026	1.00024
150	1.00080	1. "	1.00031	1.00032
100	1.00133	1.00060	1.00043	1.00044

cyc/sec. increase in frequency from that at 300 volts

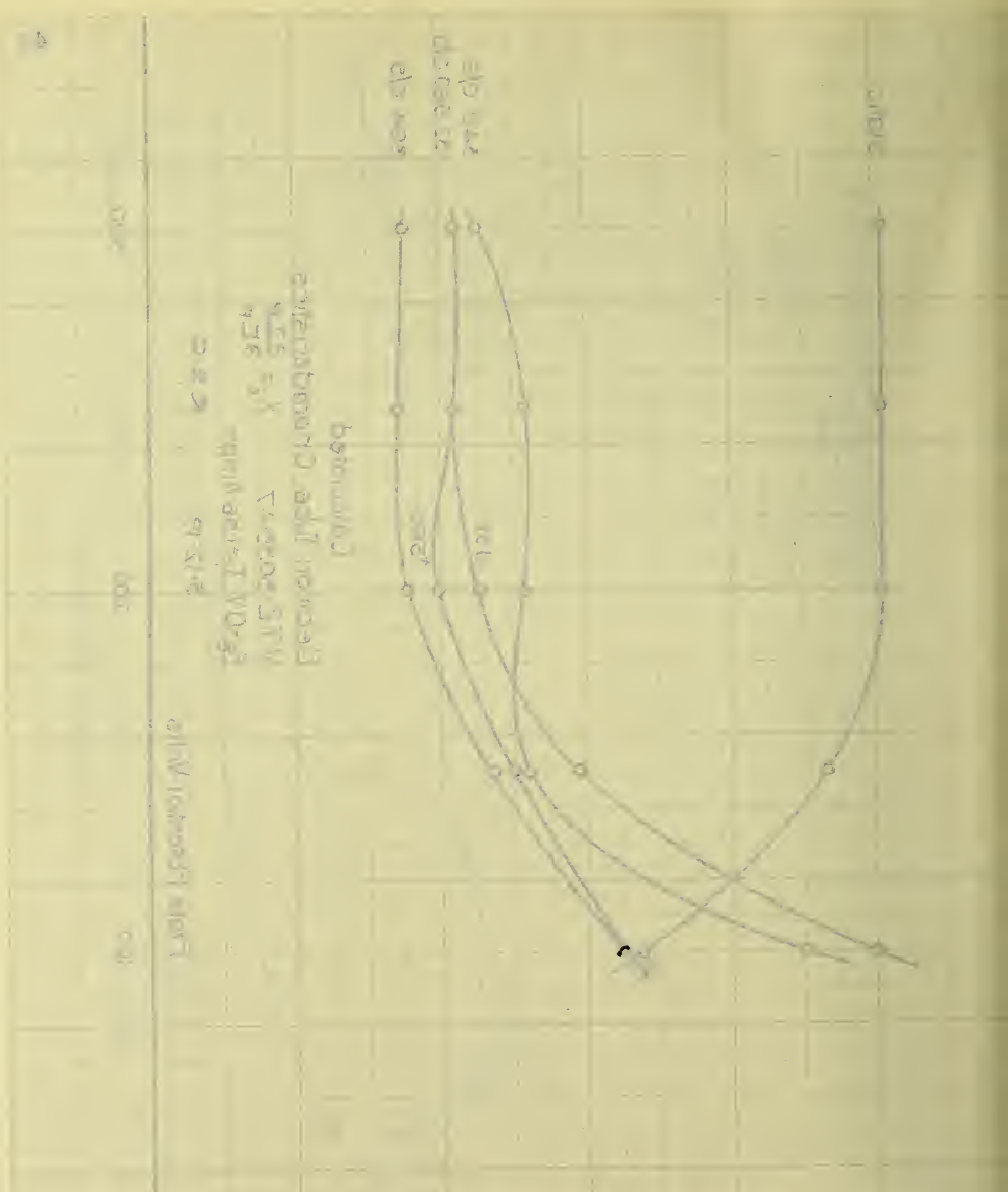
300	0.000	0.000	0.000	0.000
250	0.000	0.031	0.000	0.000
200	0.005	"	- 0.001	0.009
150	0.032	"	0.002	0.078
100	0.102	0.102	0.084	0.182

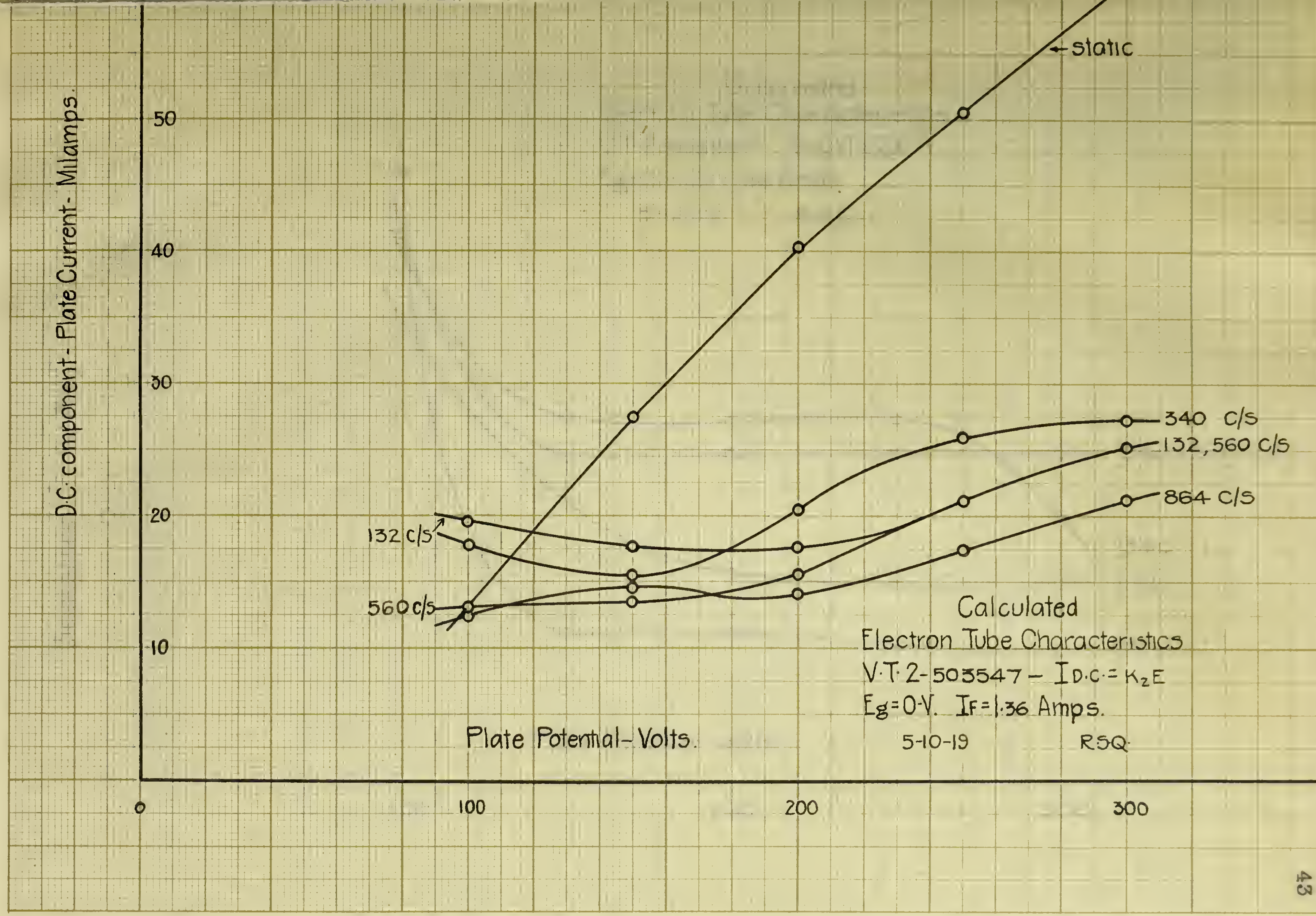

Electron-Tube Characteristics
V·T·2 503547
$E_g = 0$ V.
$I_F = 1.36$ A.
$E_p = 300$ V.
5-8-19
$K_1 = \frac{\partial I_p}{\partial E_g}$
$K_2 = \frac{\partial I_p}{\partial E_p}$
R.S.Q.
K_2
K_1
$10^3 K_1$
$10^4 K_2$
2.0
1.0
200
400
600
800
cycles per sec.



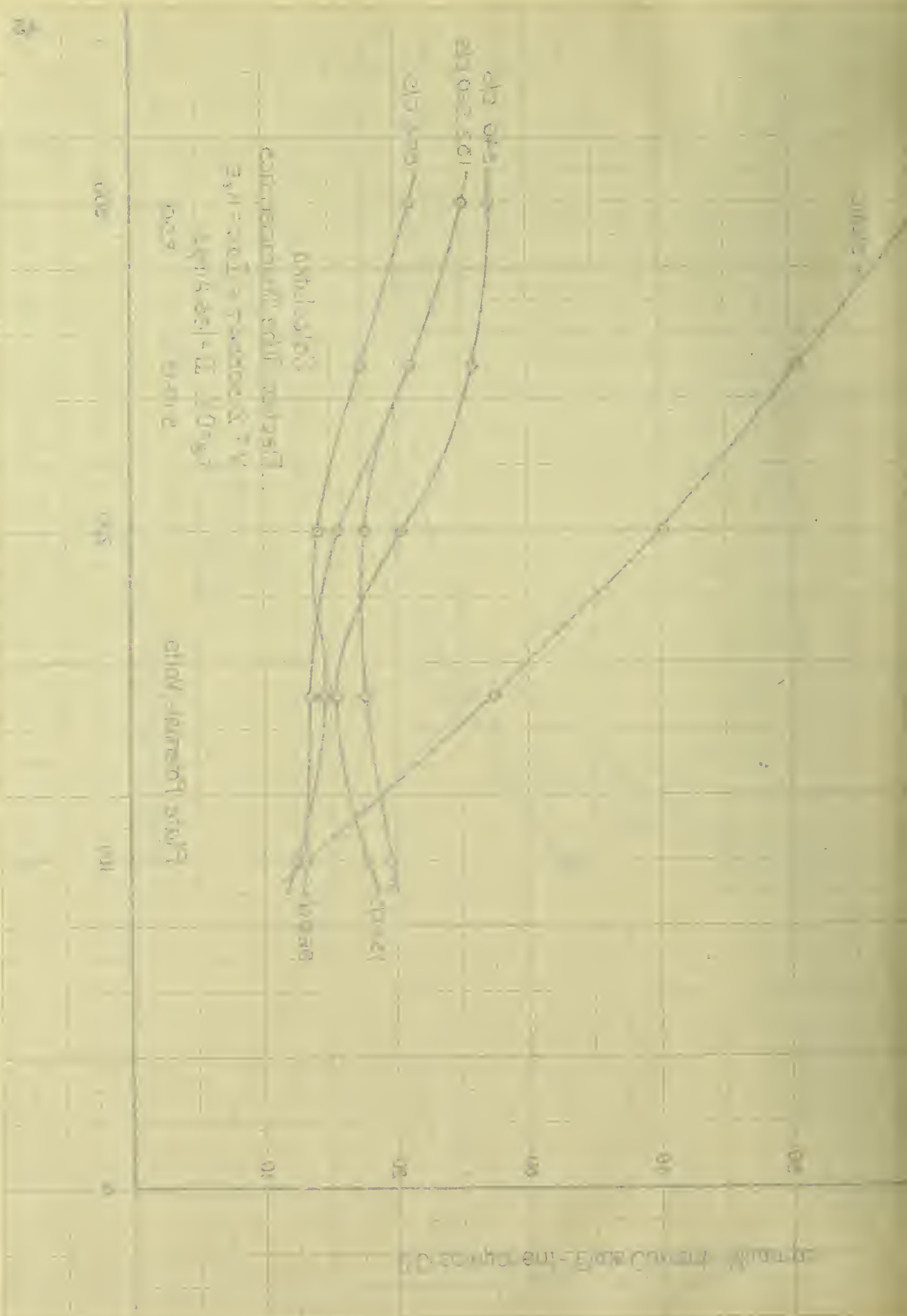


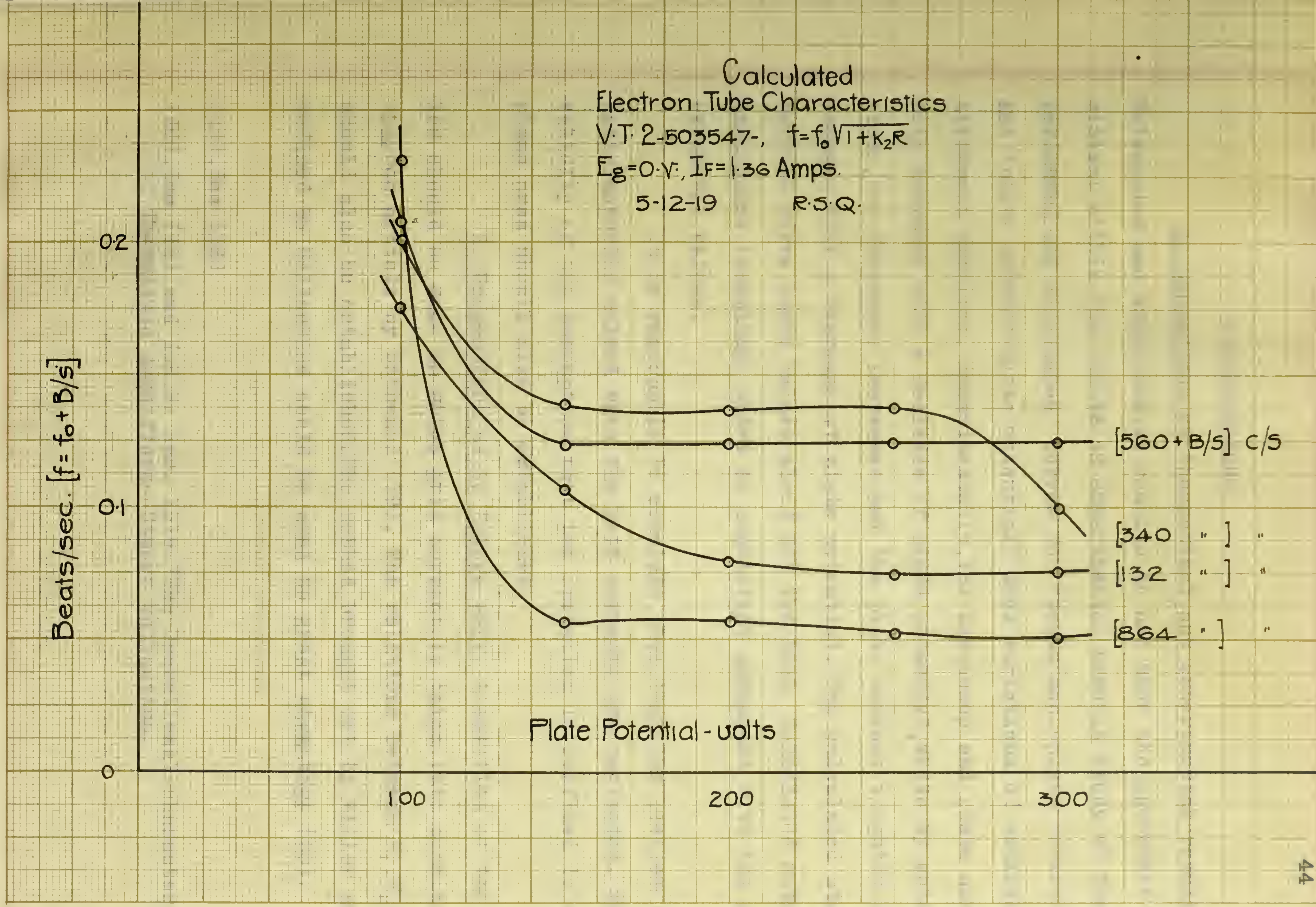
2×10⁻⁴
1×10⁻⁴
K2
static
340 c/s
132,560 c/s
864 c/s
↓132
↑560
0
100
200
300
Plate Potential-Volts
Calculated
Electron Tube Characteristics
V·T·2-503547.
$K_2 = \frac{\partial I_p}{\partial E_p}$
$E_g = 0$ V., $I_f = 1{\cdot}36$ Amps.
5-12-19
R·S·Q.



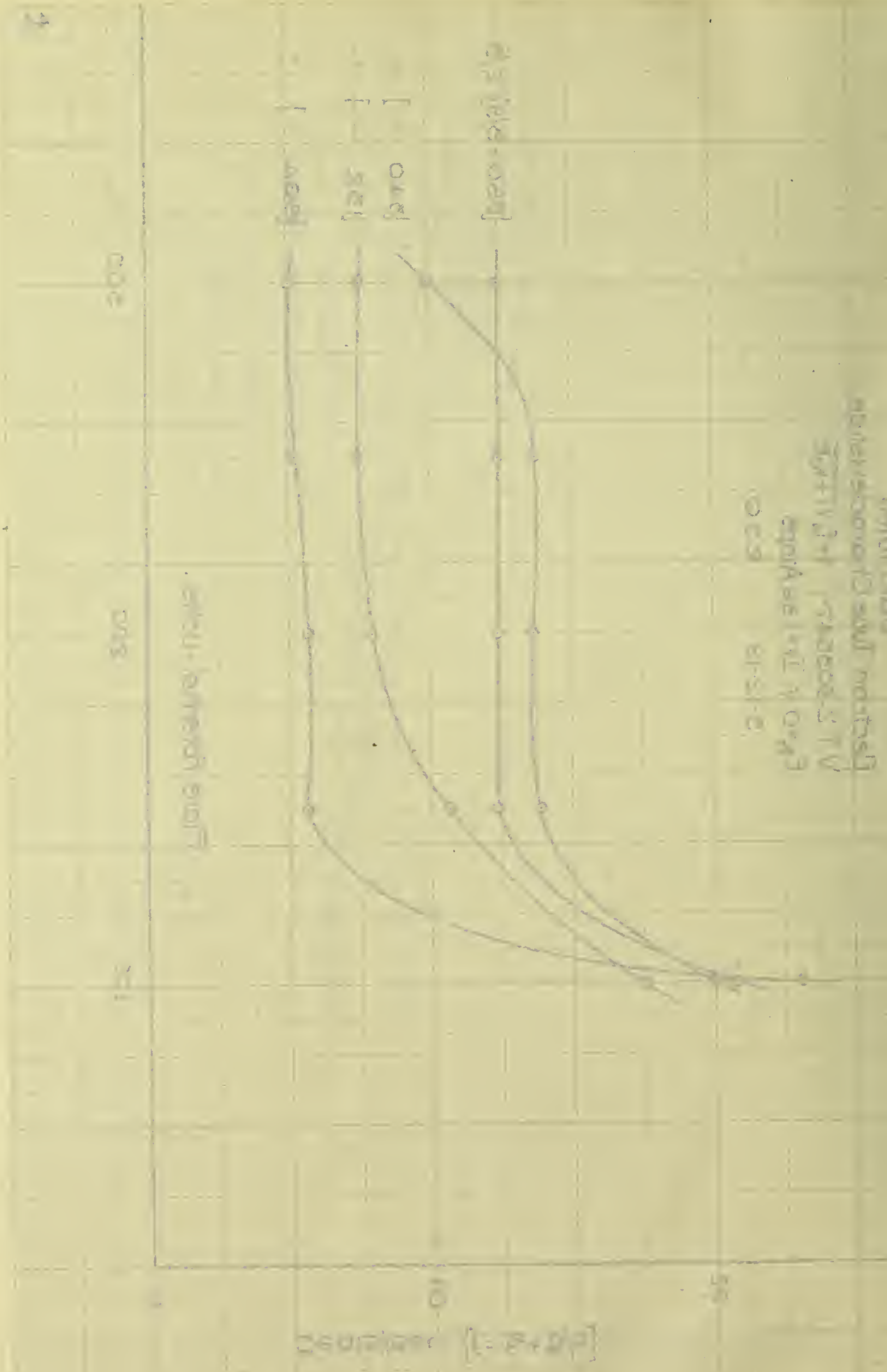


D.C. component - Plate Current - Milamps.
50
40
30
20
10
0
100
200
300
Plate Potential - Volts.
static
340 C/S
132, 560 C/S
864 C/S
132 C/S
560 C/S
Calculated
Electron Tube Characteristics
V.T. 2-503547 – $I_{D.C.} = K_2E$
E_g = 0 V. I_F = 1.36 Amps.
5-10-19
RSQ





Calculated
Electron Tube Characteristics
V.T. 2-503547-, $f = f_0\sqrt{1+K_2R}$
E_g=0 V., I_F=1.36 Amps.
5-12-19
R.S.Q.
0.2
0.1
0
Beats/sec. [f = f_0 + B/s]
100
200
300
Plate Potential - volts
[560 + B/s] c/s
[340 "] "
[132 "] "
[864 "] "



V CONCLUSIONS

1. Comparison of theoretical and experimental results. Calculated and experimental results do not show the agreement consistent within the limits of experimental error. A study of the experimental and calculated curves for "beats/sec.-plate potential" and "plate current-plate potential" show variations of entirely different families. Experimentally, the frequency and plate current both decrease with a decrease of plate potential, while by calculation, the frequency increases, and the plate current slightly decreases with a decrease of plate potential. The calculated static current curve bears values about 50% too high. Calculated mutual inductance (coupling) shows no consistent agreement with the experimental values.

It is reasonable to conclude then that the problem is not satisfactorily solved when the grid currents are neglected. The validity of the assumption that the operation is confined to a plane area should also be established.

2. Suggestions as to future work. A solution of the problem should be made in which grid current is taken into consideration. See article by Bethenod (19). The relations between K_1, K_2 and f" should also be established. The method brought out by Miller and refined by Ballantine could be used to great advantage (20).

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(19). See (15)

(20). See (18) and I.R.E. Apr. 1919. "The Operational characteristics of Thermionic Amplifiers.--Stuart Ballantine.

Relations between wave-form and amplitude of oscillation and characteristics should be established.

The opinion of previous investigators is that gas free tubes are the only ones which will give consistent operation. Such tubes should therefore be used in all studies.

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